SECTION 3.0
MASS WASTING
ASSESSMENT

ACME WATERSHED ANALYSIS
MASS WASTING MODULE

The following chapter addresses the results of the mass wasting module of the Acme Watershed Analysis. This assessment was performed in accordance with Chapter 222-22 WAC and the Standard Methodology for Conducting Watershed Analysis, Version 2.1, Washington Forest Practices Board Manual, 1994.

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3.1 INTRODUCTION/GEOLOGICAL OVERVIEW

The Level 2 mass wasting assessment of the Acme WAU was conducted in accordance with the Washington Forest Practices Board Standard Methodology for Conducting Watershed Analysis Mass Wasting Module version 2.1 (November, 1994). This assessment also draws on previous analyses of slope instability in the Acme area including Easterbrook (1983), Syverson (1984), Buchanan (1988), Benda (1989), Thorson (1992), Raines et al. (1996), and Benda et al. (1997/1998). Information on locations of slope instability for a portion of the WAU was provided by River Farm, Evergreen Land Trust (O'Neil, 1996). The initial analysis took place in 1994 through 1995. Subsequent slope stability analyses occurred in 1998.

The Acme WAU is composed of three major geologic units (Figure 3-1). The Chuckanut Formation, composed of Late Cretaceous - Early Tertiary sandstone, shale, and conglomerate underlies the northern portion of the Acme WAU. Metamorphic rocks of phyllite and minor amounts of greenschist, serpentine, and metagraywacke occur in the approximate southern one-half of the WAU. The Chuckanut - phyllite contact runs approximately northeast - southwest and is located near the town of Acme and intersects the Van Zandt Dike north of Tinling Creek. The floodplain is composed of recent alluvium (i.e. Holocene age) that originated from the Nooksack River and its tributaries.

The mechanically-stronger sedimentary rock of the Chuckanut Formation (relative to phyllite) creates the steep hillslopes found in the northern portion of the WAU including those in Standard and Sygitowicz Creeks in the west, and the Van Zandt Dike in the east. As a consequence, shallow landslides, and debris flows in first- and second-order channels are concentrated in the sandstone formation. In contrast, the weaker phyllite bedrock is more easily weathered and fractured, leading to the formation of lower-gradient hillslopes. Deep-seated landslides have formed within the weaker phyllite bedrock although shallow landsliding is also common in inner gorges.

The single largest landform in the Acme WAU is the terrace and floodplain complex of the South Fork Nooksack River which comprises approximately 40% of the WAU. This major depositional area intercepts sediment originating from the small mountain tributaries creating alluvial and debris flow fans. Hence, much of the sediment produced in the Acme WAU becomes stored in fans or on floodplains and does not reach the main river (see Channel Assessment). It was estimated that the Acme WAU contributes less than 10% of the total sediment supply to the South Fork Nooksack River at its location in the WAU (see Channel Assessment).

3.2 TYPES OF MASS WASTING

Shallow-rapid landslides and debris flows are the dominant form of mass wasting. The majority of shallow landsliding occurs in convergent areas (bedrock hollows) located at the heads of first-order channels and within inner gorges (which contain

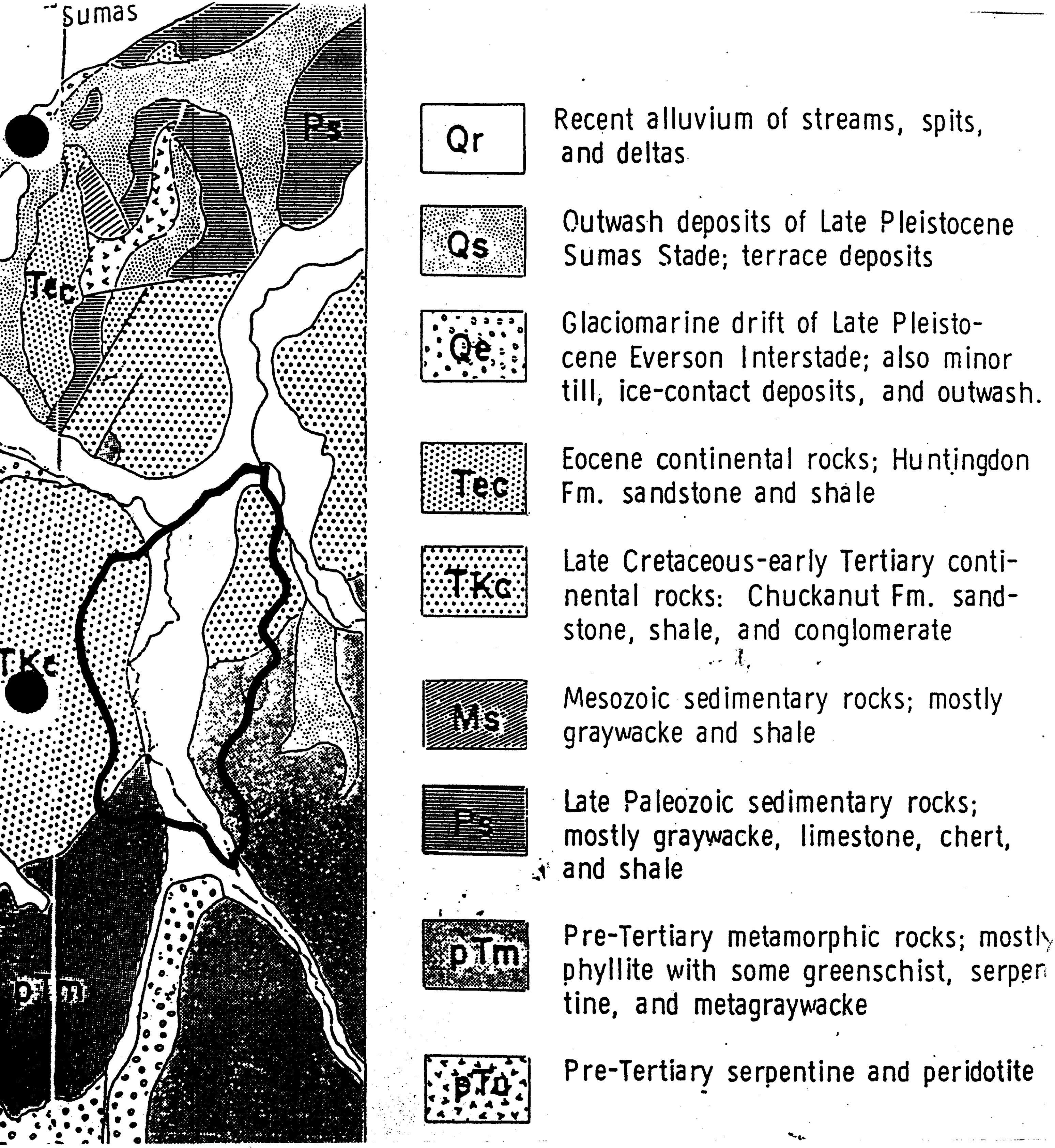

Figure 3-1 Geologic map of the Acme WAU (from Easterbrook, 1971).

all slope forms). Sites of shallow landsliding in this terrain have also been referred to as "debris chutes" (Easterbrook, 1983) and "wedges" (Buchanan, 1988). Debris flows triggered by shallow landslides are concentrated in first- and second-order channels (Benda and Cundy, 1990). Dam-break floods (using the terminology of Benda and Zhang, 1989; Coho and Burges, 1993) have occurred in most of the major mountain tributaries and they were not differentiated from debris flows in the landslide inventory. All long-runout mass wasting events were categorized as debris flows. Volume of organic debris in low-order channels, which can be increased by logging activities (at least historically) can increase the magnitude (and destructiveness) of dam-break floods (debris torrents) (Syverson, 1984).

Deep-seated landsliding in the WAU is concentrated in the phyllite formation in the southwest portion of the WAU. A convexity or bulge in the longitudinal profile of Jones Creek (see Channel Assessment) and hummocky topography strongly suggest the existence of a historic deep-seated landslide centered in the Jones Creek basin. Landsliding is concentrated in colluvium in the inner gorge of Jones Creek, an area also susceptible to deep-seated landsliding. Smaller deep-seated landslides that were observed during field surveys in the inner gorges of Jones and McCarty Creek basins are very difficult to detect remotely from aerial photographs of forest canopy. At least one small deep-seated landslide intersects State Highway 9 south of the town of Acme.

There is evidence (old deposits) of an ancient, large, deep-seated landslide along the Van Zandt Dike in the northeast portion of the WAU (T38N, R5E, Section 4 and 9). In addition, there is currently active bedrock fracturing near the top of the Van Zandt Dike in Section 10 (i.e. Devils Slide). Such "mountain splitting" is presumably controlled by large tensional forces near the top of ridges which create rock avalanches that deposit near the base of the dike.

3.3 ANALYSIS OF MASS WASTING

3.3.1 Air Photo Landslide Inventory

Mass wasting in the Acme WAU was inventoried using aerial photographs from 1970, 1978, 1983, 1987, 1991, 1995, and by field observations in 1994 and 1998. Landslides inventoried in Jones Creek Basin by Thorsen (1992) were included. Mass wasting was differentiated into shallow-rapid landslides, debris flows, deep-seated landslides which occurs predominantly in the phyllite bedrock, and sandstone bedrock slab failures (Devil's Slide). Many of the large debris-laden events that travelled to the mouths of many of the mountain tributaries over the aerial photo period of record were likely dam-break floods. In the absence of recent events required for field verification, all long-runout mass wasting events were included in the debris flow category. Small, deep-seated landslides may have been mapped as shallow landslides in the inventory, particularly in inner gorges because aerial photographs do not have sufficient resolution to differentiate among the different slide mechanisms.

Hillslope characteristics were inventoried at each landslide using primarily aerial photography and topographic maps. Characteristics included slope gradient, slope form (i.e., convergent, divergent and planar), general landform (i.e., inner gorge), lithology, and whether sediment was deposited directly to stream channels and the order of the stream. One hundred and ninety-one landslides were inventoried in the Acme WAU using the aerial photo record (Table 3-1 (DNR Form A-1) and Figure 3-2 (DNR Map A-1)). Some small landslides may not have been mapped during the inventory. Nevertheless, a sufficient number were mapped and later observed in the field to determine the landforms most prone to failure, the objective of the inventory in this stability assessment. Landslide activity was concentrated in the late 1970s and during the mid-1980s coinciding with timber harvest, logging roads, and large winter storms.

The majority of shallow-rapid landslides and debris flows in the Acme basin occurred within bedrock hollows, convergent heads of first-order channels (channel heads) also referred to as "wedge" (Buchanan, 1988), and inner gorges (which may contain any slope form); this is consistent with numerous other landslide inventories in the region (Warnick Watershed Analysis, 1994; Collins et al., 1994; Jordon-Boulder Watershed Analysis, 1996). Sixty-five percent of the landslide sites have gradients greater than or equal to 36 degrees based on 1:24,000-scale topographic maps. However, field observations of landslide sites during this analysis and a study of landsliding in southwest Washington (Dragovich and Brunengo, 1994; Dragovich et al., 1993), both indicate that map-based gradients underestimate the actual hillslope gradients by approximately 4 to 8 degrees on average. For example, many bedrock hollows and virtually all inner gorges are not resolved on a 1:24,000-scale topographic map. To account for the underestimation of slope gradient from topographic maps, the inventoried landslides in hollows and inner gorges were increased an average of 5 degrees. Using this correction factor, 88% of the inventoried landslides had slopes greater than 36 degrees and 12% had slopes between 31 and 35 degrees. Therefore, the proportion of landslides that occurred on slopes greater than or equal to 36 degrees likely range between 65 and 88%, while the proportion in the 31 to 35 degree category ranged between 35% and 12%. This indicates that failures are between 2 and 7 times more likely to occur in hillslopes greater than or equal to 36 degrees.

3.3.2 Field Survey of Landslide Sites in Convergent Areas

A field survey of historical failures that had occurred in clearcuts was conducted in 1998 to better define the slope gradients associated with shallow landsliding. The study was confined to shallow landslides that had occurred in the Chuckanut sandstone formation. Landslide sites selected for field review were selected from the landslide inventory based on their location in old clearcut areas (slides associated with roads or landings were not selected) and on access (survey was conducted in December, 1998). To determine the field-based frequency distribution of landslide gradients in the Acme area, 14 landslides were visited (Figures 3-3 and 3-4).

At each landslide headscarp in convergent areas (bedrock hollows or wedges), the slope gradient was measured with a clinometer uphill towards the scarp and downhill towards the runout track (gradients were measured over distances of several tens of meters). These two measurements were averaged to produce a single average slope gradient (Table 3-2). The frequency histogram of the measured slope gradients are plotted in Figure 3-5. To this population was added five landslides studied by Buchanan (1988), including sites W-1, W-2, DD-1, DD-2, and DD-3. Widths of landslide scars were also visually estimated (Table 3-2).

Seventeen slides in hollows (all of which delivered sediment to channels), or 89%, had gradients greater than or equal to 36° (73%). Of the two remaining slides, one had a gradient of 35° (70%) and the other 32° (62%); the latter slide may have been associated with road drainage. The mean gradient of all nineteen slides is 37.5° (77%). The field survey concluded that the slope correction factor used in the aerial photograph based landslide inventory which placed 88% of landslides (all slides in this case) in a category of > =36 degrees was appropriate. Furthermore, the field analysis should be considered the most accurate representation of hillslope gradients necessary to trigger shallow failures in convergent areas.

It was observed in the field that several of the landslide scars occurred in shallow bedrock hollows (e.g., non pronounced bedrock concavities); this was also found by Buchanan (1988) who referred to them as "wedges." In the field, landslides in wedges were usually connected to an incised first-order stream valley which allowed propagation of the slide as a debris flow. Hence, to aid in the field detection of all steep convergent areas prone to failure, one or more soil wedges should be anticipated at the heads of steep, incised first-order channels, in addition to more well developed bedrock hollows. In addition, widths of landslide scars ranged from 4 m (13 ft) to 12 m (40 ft) and averaged 7 m (23 ft). This information could be used to help determine the size of leave areas in hollows for the purpose of maintaining buffer strips.

A small proportion of landslide-prone bedrock hollows have slopes less than 36 degrees, although slope gradients should almost always succeed 31 degrees. The stability of these lower gradient hollows should be considered greater than hollows > =36 degrees (e.g., Figure 3-5).

The concentration of landsliding on hillslopes greater than 36 degrees is consistent with other landslide studies in the area. During a landslide study in the Smith Creek watershed located immediately adjacent (west) of the Acme WAU, Syverson (1984) found that 48% of landslides occurred on 30 - 40 degree slopes and 52% on slopes

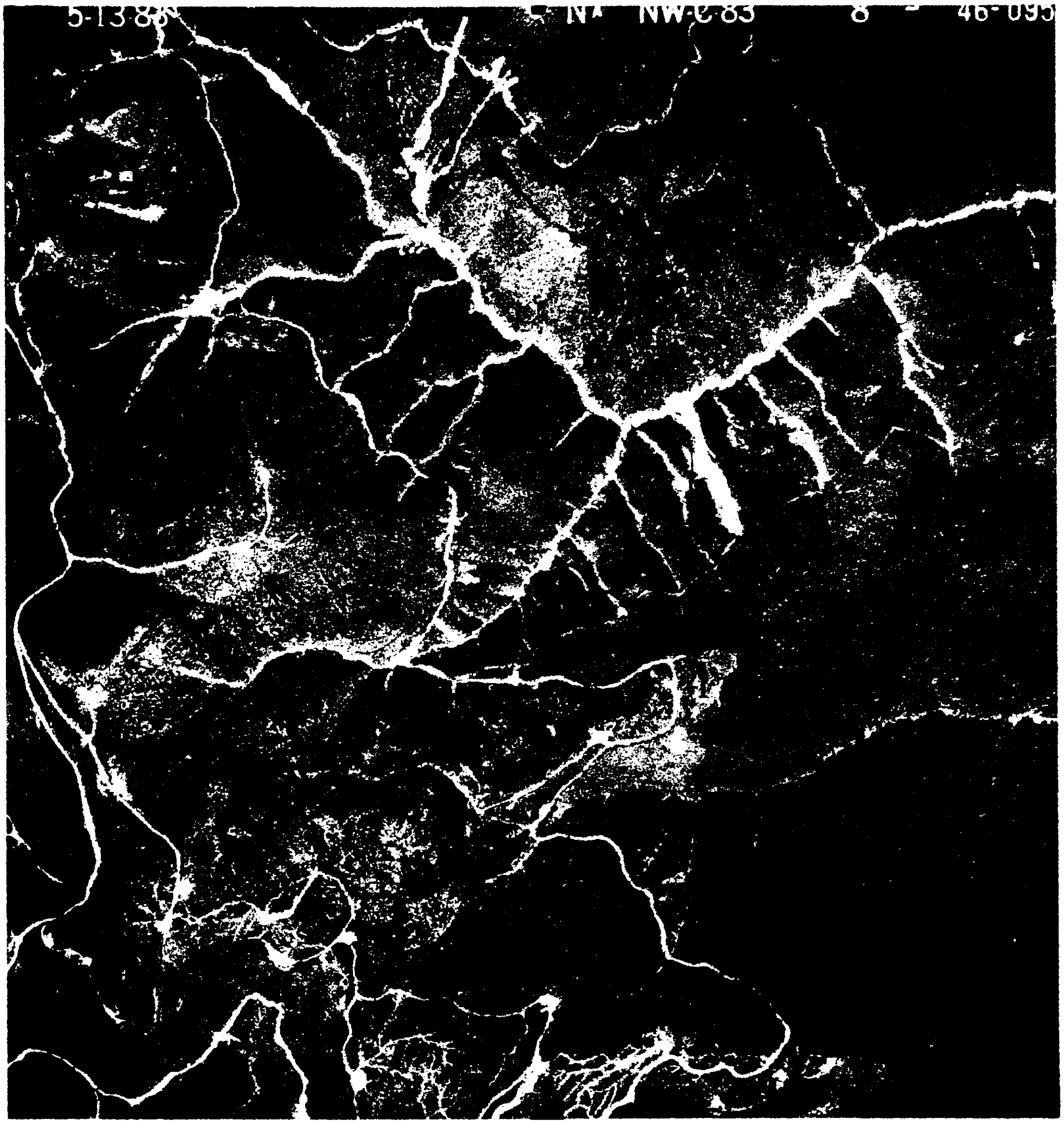

Figure 3-3. Upper watershed areas in the Acme WAU showing the locations of recent landslides where measurements of headscarp gradients were made.

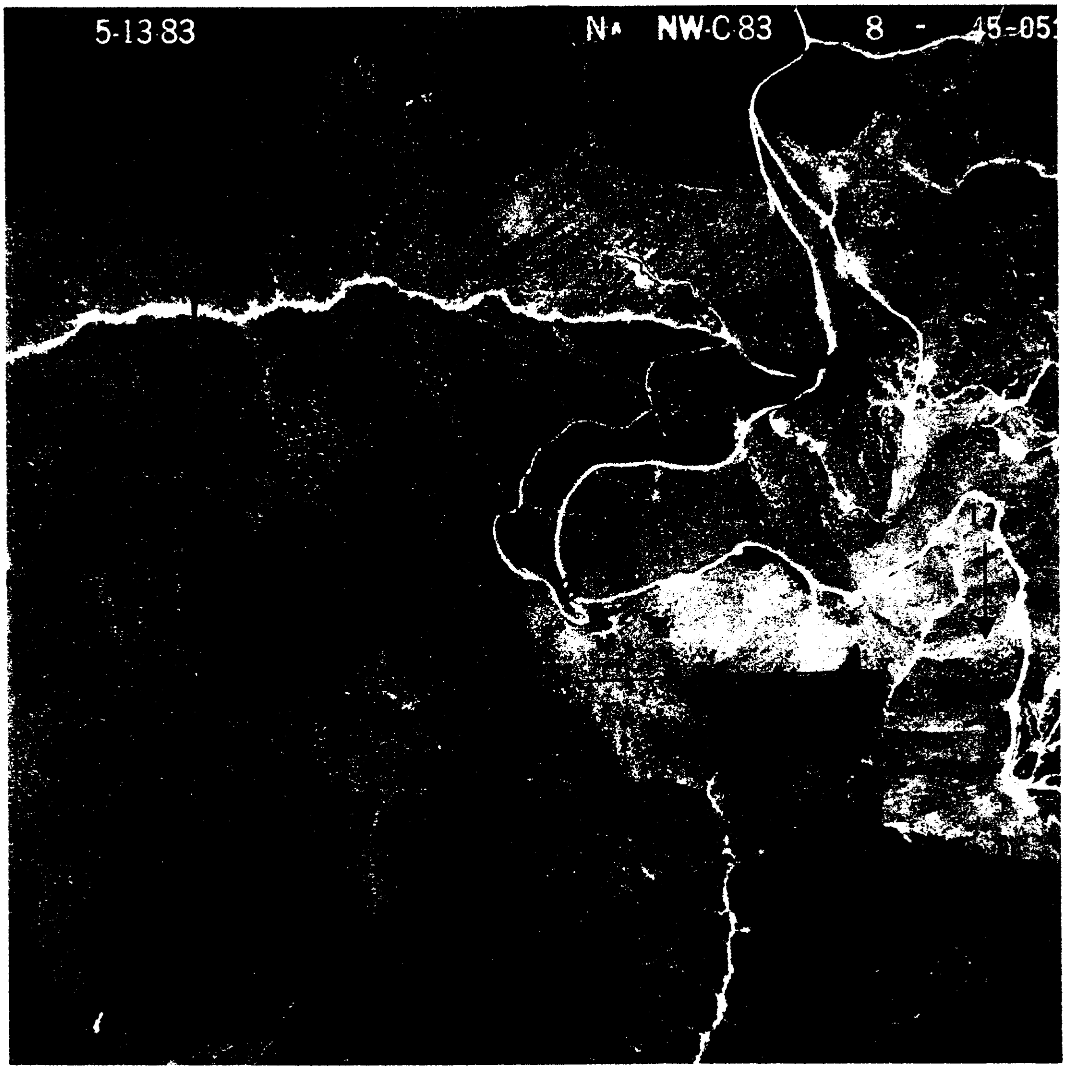

Figure 3-4. Upper watershed areas draining into Lake Whatcom where gradients of landslides were obtained.

Mass Wasting Map Unit Number	Landslide I.D. Number	Landslide Type	Aerial Photo Year	Sediment Delivered to stream (Y,N,name or order)	Associated Land-use Activity	Slope Form	Hillslope Gradient (degrees)	Township (North)	Range (East)	Section
2	166	SR	1983	4	mature forest	inner gorge	>/= 36	37	4	1
8	167	SR\DF	1991	N	road	hollow	>/= 36	37	5	6
8	168	SR	1991	N	road	hollow	>/= 36	37	5	6
8	169	SR	1991	N	road	hollow	>/= 36	37	5	6
2	170	DS	1994	N	mature forest	inner gorge	>/= 36	37	5	7
2	171	DS	1994	4	none	inner gorge	>/= 36	37	5	7
2	172	DS	1994	4	none	inner gorge	>/= 36	37	5	7
2	173	DS	1994	4	none	inner gorge	>/= 36	37	4	12
2	174	DS	1994	4	none	inner gorge	>/= 36	37	4	12
9	175	DS	1994	4	none	inner gorge	>/= 36	37	4	11
1	176	SR	1994	S Fk Nooksack	road	hollow	>/= 36	38	5	30
1	177	SR	1994	S Fk Nooksack	road	hollow	>/= 36	38	5	30
1	178	SR	1994	S Fk Nooksack	road	hollow	>/= 36	38	5	30
2	179	SR\DF	1994	S Fk Nooksack	clearcut	inner gorge	>/= 36	38	5	30
8	180	DF	1995	N	mature forest	hollow	31-35	37	4	7
8	181	DS	1995	N	young forest	hollow	31-35	38	5	33
2	182	DS	1995	Jones Creek	mature forest	inner gorge	31-35	37	5	7
2	183	DS	1995	Jones Creek	mature forest	inner gorge	31-35	37	5	7
8	184	SR	1995	N	road	hollow	31-35	37	5	6
8	185	SR	1995	N	road	hollow	31-35	37	5	6
1	186	SR	1995	3	mature forest	inner gorge	>/= 36	38	4	36
1	187	SR	1995	3	mature forest	inner gorge	>/= 36	38	4	36
1	188	SR	1995	3	mature forest	inner gorge	>/= 36	38	4	36
7	189	SR	1995	N	clearcut	hollow	31-35	38	5	21
7	190	SR	1995	N	clearcut	hollow	31-35	38	5	21
2	191	SR	1995	4	mature forest	inner gorge	>/= 36	37	4	1
		(SR = shallow-rapid, DS = deep-seated, DF = debris flow)								

Table 3-1 (DNR Form A-1) cont.

Mass Wasting Map Unit Number	Landslide I.D. Number	Landslide Type	Aerial Photo Year	Sediment Delivered to stream (Y,N,name or order)	Associated Land-use Activity	Slope Form	Hillslope Gradient (degrees)	Township (North)	Range (East)	Section
7	133	SR	1991	1	road	hollow	>/= 36	38	5	3
7	134	SR	1991	1	road	hollow	>/= 36	38	5	3
7	135	SR	1991	N	clearcut	hollow	>/= 36	38	5	3
7	136	SR	1991	N	clearcut	hollow	>/= 36	38	5	3
7	137	SR	1991	N	clearcut	hollow	>/= 36	38	5	3
7	138	SR	1991	1	clearcut	hollow	>/= 36	38	5	3
7	139	SR	1991	1	clearcut	hollow	31-35	38	5	4
7	140	SR	1991	N	clearcut	hollow	>/= 36	38	5	3
7	141	SR	1991	N	clearcut	hollow	>/= 36	38	5	3
7	142	SR	1991	1	mature forest	hollow	31-35	38	5	3
1	143	SR	1991	N	road	hollow	31-35	38	4	14
8	144	SR	1991	1	road	hollow	>/= 36	38	4	14
1	145	SR	1991	4	road	hollow	>/= 36	38	4	14
2	146	SR	1991	4	mature forest	inner gorge	>/= 36	37	4	11
8	147	SR\DF	1991	1	clearcut	inner gorge	>/= 36	38	4	36
2	148	SR	1991	4	mature forest	inner gorge	>/= 36	38	4	25
2	149	DS	1991	4	mature forest	inner gorge	>/= 36	38	4	24
1	150	SR\DF	1983	4	road	hollow	31-35	37	4	11
2	151	SR	1983	4	mature forest	inner gorge	>/= 36	37	4	11
2	152	SR	1983	4	mature forest	inner gorge	>/= 36	37	4	11
3a	153	SR\DF	1983	4	mature forest	hollow	>/= 36	37	4	1
2	154	SR\DF	1983	3	road	hollow	>/= 36	38	4	26
3b	155	SR\DF	1983	3	road	hollow	>/= 36	38	4	26
3a	156	SR\DF	1983	4	road	hollow	>/= 36	38	4	26
3b	157	SR	1983	N	road	hollow	>/= 36	38	4	26
3b	158	SR	1983	3	road	hollow	>/= 36	38	4	26
2	159	SR	1983	3	road	hollow	>/= 36	38	4	26
1	160	SR\DF	1983	4	road	hollow	>/= 36	38	4	26
1	161	SR\DF	1983	4	road	hollow	>/= 36	38	4	25
1	162	SR	1983	4	road	hollow	>/= 36	38	4	25
8	163	SR\DF	1983	4	mature forest	hollow	>/= 36	37	4	1
2	164	SR	1983	4	mature forest	inner gorge	>/= 36	37	4	1
8	165	SR\DF	1983	4	mature forest	inner gorge	>/= 36	37	4	1

Table 3-1 (DNR Form A-1) cont.

Mass Wasting Map Unit Number	Landslide I.D. Number	Landslide Type	Aerial Photo Year	Sediment Delivered to stream (Y,N,name or order)	Associated Land-use Activity	Slope Form	Hillslope Gradient (degrees)	Township (North)	Range (East)	Section
1	100	SR\DF	1987	4	road	hollow	>/= 36	38	4	23
1	101	SR\DF	1987	4	road	hollow	>/= 36	38	4	23
1	102	SR\DF	1987	4	road	hollow	>/= 36	38	4	24
3b	103	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	23
3a	104	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	23
1	105	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	24
1	106	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	23
1	107	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	23
1	108	SR\DF	1987	4	road	hollow	>/= 36	38	4	23
1	109	SR\DF	1987	4	road	hollow	>/= 36	38	4	14
1	110	SR\DF	1987	4	road	hollow	>/= 36	38	4	23
1	111	SR\DF	1987	4	road	hollow	>/= 36	38	4	14
1	112	SR\DF	1987	4	road	hollow	>/= 36	38	4	14
1	113	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	15
1	114	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	22
1	115	SR\DF	1987	4	road	hollow	>/= 36	38	4	14
1	116	SR	1987	N	clearcut	inner gorge	>/= 36	38	4	14
1	117	SR	1987	N	clearcut	inner gorge	>/= 36	38	4	14
1	118	SR	1987	N	clearcut	inner gorge	>/= 36	38	4	14
1	119	SR	1987	3	clearcut	inner gorge	>/= 36	38	4	14
1	120	SR	1987	N	clearcut	inner gorge	>/= 36	38	4	14
1	121	SR	1987	N	clearcut	inner gorge	>/= 36	38	4	14
2	122	SR\DF	1987	3	road	hollow	>/= 36	38	4	14
1	123	SR\DF	1987	3	clearcut	hollow	>/= 36	38	4	14
2	124	SR	1987	3	clearcut	hollow	>/= 36	38	4	14
1	125	SR	1987	N	road	hollow	>/= 36	38	4	14
1	126	SR	1987	3	clearcut	inner gorge	>/= 36	38	4	
1	127	SR	1987	3	road	hollow	31-35	38	4	14
2	128	SR	1991	4	mature forest	hollow	>/= 36	38	4	1
6	129	SR	1991	1	mature forest	hollow	31-35	38	5	16
6	130	SR	1991	1	mature forest	hollow	>/= 36	38	5	6
6	131	SR	1991	3	mature forest	inner gorge	>/= 36	38	5	9
7	132	SR	1991	1	road	hollow	>/= 36	38	5	3

Table 3-1 (DNR Form A-1) cont.

Mass Wasting Map Unit Number	Landslide I.D. Number	Landslide Type	Aerial Photo Year	Sediment Delivered to stream (Y,N,name or order)	Associated Land-use Activity	Slope Form	Hillslope Gradient (degrees)	Township (North)	Range (East)	Section
6	67	SR	1978	N	mature forest	inner gorge	>/= 36	38	5	16
6	68	SR\DF	1978	N	clearcut	inner gorge	>/= 36	38	5	10
6	69	SR\DF	1978	N	mature forest	inner gorge	>/= 36	38	5	16
6	70	SR	1978	N	mature forest	inner gorge	>/= 36	38	5	16
6	71	SR	1978	N	mature forest	inner gorge	>/= 36	38	5	16
6	72	SR	1978	N	mature forest	inner gorge	>/= 36	38	5	16
6	73	SR	1978	N	mature forest	hollow	>/= 36	38	5	10
1	74	SR\DF	1978	4	mature forest	hollow	31-35	38	4	13
1	75	SR\DF	1978	3	road	hollow	>/= 36	38	4	26
1	76	SR\DF	1978	3	road	hollow	>/= 36	38	4	26
3a	77	SR	1978	N	clearcut	hollow	31-35	38	4	26
2	78	SR	1978	2	clearcut	inner gorge	>/= 36	38	4	26
8	79	SR	1983	N	mature forest	inner gorge	>/= 36	38	5	20
6	80	SR	1983	N	mature forest	inner gorge	>/= 36	38	5	16
3a	81	SR	1983	5	mature forest	hollow	31-35	38	4	18
8	82	SR	1983	N	clearcut	hollow	31-35	38	5	7
8	83	SR	1983	N	clearcut	hollow	31-35	38	5	7
7	84	SR	1983	N	mature forest	hollow	>/= 36	38	5	10
3a	85	SR	1987	4	mature forest	hollow	31-35	37	4	1
1	86	SR\DF	1987	4	mature forest	inner gorge	>/= 36	37	4	1
3a	87	SR\DF	1987	4	mature forest	hollow	>/= 36	38	4	36
2	88	SR	1987	4	mature forest	inner gorge	>/= 36	38	4	25
3a	89	SR\DF	1987	4	young forest	hollow	>/= 36	38	4	36
3a	90	SR\DF	1987	4	young forest	hollow	>/= 36	38	4	26
2	91	SR\DF	1987	4	young forest	hollow	>/= 36	38	4	26
3b	92	SR	1987	3	clearcut	hollow	31-35	38	4	26
1	93	SR	1987	3	road	hollow	>/= 36	38	4	26
1	94	SR\DF	1987	4	clearcut	hollow	>/= 36	38	4	24
1	95	SR\DF	1987	4	road	hollow	>/= 36	38	4	24
1	96	SR\DF	1987	4	road	hollow	>/= 36	38	4	24
2	97	SR\DF	1987	4	clearcut	planar	>/= 36	38	4	23
1	98	SR\DF	1987	4	road	hollow	>/= 36	38	4	23
1	99	SR\DF	1987	4	road	hollow	>/= 36	38	4	23

Table 3-1 (DNR Form A-1) cont.

Mass Wasting Map Unit Number	Landslide I.D. Number	Landslide Type	Aerial Photo Year	Sediment Delivered to stream (Y,N,name or order)	Associated Land-use Activity	Slope Form	Hillslope Gradient (degrees)	Township (North)	Range (East)	Section
1	34	SR\DF	1978	3	clearcut	hollow	>/= 36	38	4	23
3a	35	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
3a	36	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
3a	37	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
1	38	SR	1978	3	road	hollow	>/= 36	38	4	23
1	39	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
3b	40	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
3a	41	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
3a	42	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
1	43	SR	1978	N	road	hollow	>/= 36	38	4	23
1	44	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
1	45	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
1	46	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
1	47	SR	1978	3	road	hollow	>/= 36	38	4	23
1	48	SR\DF	1978	3	road	hollow	>/= 36	38	4	23
1	49	SR	1978	2	clearcut	inner gorge	>/= 36	38	4	23
1	50	SR	1978	2	clearcut	inner gorge	>/= 36	38	4	23
1	51	SR\DF	1978	4	road	hollow	31-35	38	4	23
1	52	SR\DF	1978	4	road	hollow	>/= 36	38	4	14
3a	53	SR\DF	1978	4	road	hollow	>/= 36	38	4	14
2	54	SR\DF	1978	3	road	hollow	>/= 36	38	4	14
1	55	SR\DF	1978	3	road	hollow	>/= 36	38	4	14
1	56	SR\DF	1978	3	road	hollow	>/= 36	38	4	14
3a	57	SR\DF	1978	3	road	hollow	>/= 36	38	4	14
1	58	SR\DF	1978	4	road	hollow	>/= 36	38	4	14
3a	59	SR\DF	1978	4	road	hollow	31-35	38	4	14
1	60	SR\DF	1978	4	road	hollow	>/= 36	38	4	26
1	61	SR\DF	1978	4	road	hollow	>/= 36	38	4	26
1	62	SR\DF	1978	4	road	hollow	>/= 36	38	4	26
1	63	SR	1978	3	road	hollow	>/= 36	38	4	25
1	64	SR\DF	1978	3	road	hollow	>/= 36	38	4	25
8	65	SR	1978	N	road	hollow	>/= 36	38	4	23
6	66	SR	1978	N	mature forest	inner gorge	>/= 36	38	5	16

Table 3-1 (DNR Form A-1) cont.

Mass Wasting Map Unit Number	Landslide I.D. Number	Landslide Type	Aerial Photo Year	Sediment Delivered to stream (Y,N,name or order)	Associated Land-use Activity	Slope Form	Hillslope Gradient (degrees)	Township (North)	Range (East)	Section
7	1	SR	1970	N	clearcut	hollow	>/= 36	38	5	33
7	2	SR	1970	N	clearcut	hollow	>/= 36	38	5	33
7	3	SR	1970	N	clearcut	hollow	>/= 36	38	5	33
7	4	SR	1970	N	clearcut	hollow	>/= 36	38	5	33
7	5	SR	1970	N	clearcut	hollow	>/= 36	38	5	3
7	6	SR	1970	N	clearcut	hollow	31-35	38	5	3
2	7	SR	1970	3	partial cut?	inner gorge	>/= 36	37	4	12
2	8	SR	1970	3	partial cut?	inner gorge	>/= 36	37	4	12
2	9	SR	1970	3	clearcut	inner gorge	>/= 36	37	4	11
2	10	SR	1970	3	clearcut	inner gorge	>/= 36	37	4	11
2	11	SR	1970	2	clearcut	hollow	31-35	37	4	11
2	12	SR	1970	2	road	planar	31-35	37	4	11
8	13	SR\DF	1970	3	clearcut	hollow	31-35	37	4	2
2	14	SR	1970	3	clearcut	inner gorge	>/= 36	37	4	2
2	15	SR	1970	3	clearcut	inner gorge	>/= 36	37	4	2
3a	16	SR	1970	3	clearcut	hollow	>/= 36	37	4	2
3a	17	SR	1970	3	clearcut	hollow	>/= 36	37	4	2
3a	18	SR	1970	3	clearcut	hollow	>/= 36	37	4	2
1	19	SR	1970	3	clearcut	inner gorge	>/= 36	38	4	25
1	20	SR	1970	3	road	hollow	>/= 36	38	4	25
1	21	SR	1970	3	road	hollow	>/= 36	38	4	25
1	22	SR	1970	3	road	hollow	>/= 36	38	4	25
8	23	SR	1970	N	road	hollow	>/= 36	38	4	11
1	24	SR	1970	3	road	hollow	>/= 36	38	4	11
1	25	SR	1970	3	road	hollow	>/= 36	38	4	14
2	26	SR	1970	N	clearcut	hollow	>/= 36	37	4	11
2	27	SR	1970	N	clearcut	hollow	>/= 36	37	4	11
1	28	SR\DF	1978	3	road	hollow	>/= 36	38	4	14
8	29	SR	1978	N	clearcut	hollow	>/= 36	38	4	22
8	30	SR	1978	N	clearcut	hollow	31-35	38	4	22
3b	31	SR	1978	N	clearcut	hollow	>/= 36	38	4	23
1	32	SR\DF	1978	3	road	hollow	31-35	38	4	23
1	33	SR\DF	1978	3	road	hollow	>/= 36	38	4	23

Table 3-1 (DNR Form A-1)

Table 3-2. Hillslope gradients and widths of landslide scars obtained at landslide headscarps.

Landslide #	Source	Axis Gradient (degrees)	Landslide Inventory #	Inventory Gradient (degrees)	Scar Width (m)
1	This survey	39	98	>=36	6
2	This survey	37	Na[2]		5
~~8~~ 3	This survey	40	38	>=36	12
4	This survey	38	Na[2]		6
5	This survey	42	105	>=36	6
6	This survey	39	106	>=36	7
7	This survey	38	107	>=36	9
8	This survey	36	94	>=36	6
9	This survey	32[1]	96	>=36	6
10	This survey	36	95	>=36	8
11	This survey	36	34	>=36	4
12	This survey	39	104	>=36	6
13	This survey	36	Na[3]		7
14	This survey	38	Na[3]		10
15	Buchanan(1988)	39	Na[3]		
16	Buchanan(1988)	36	Na[3]		
17	Buchanan(1988)	35	Na[3]		
18	Buchanan(1988)	39	Na[3]		
19	Buchanan(1988)	37	Na[3]		

[1] could be road related

Na[2] Not included in original inventory

Na[3] Outside of original inventory area

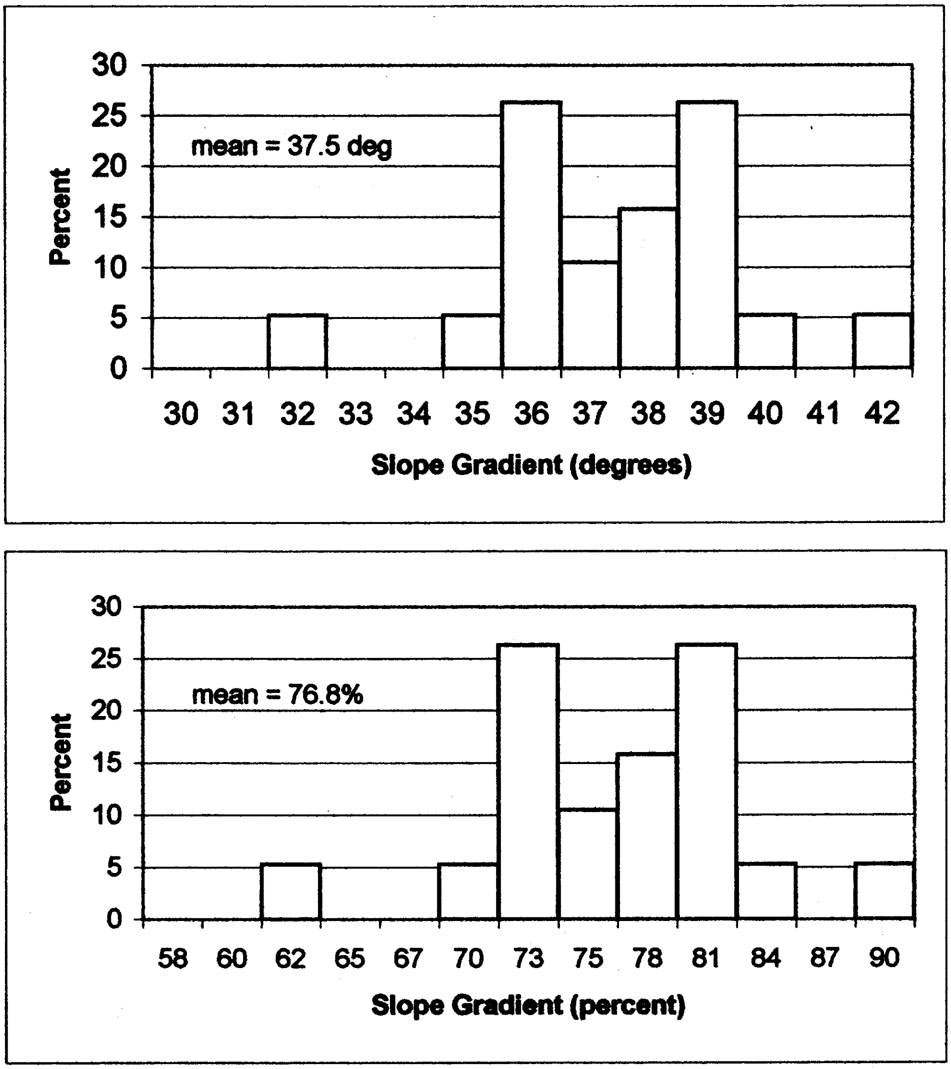

Figure 3-5. Histogram of nineteen field-measured gradients of recent landslide scars in bedrock hollows. Five of the sites were measured by Buchanan(1988).

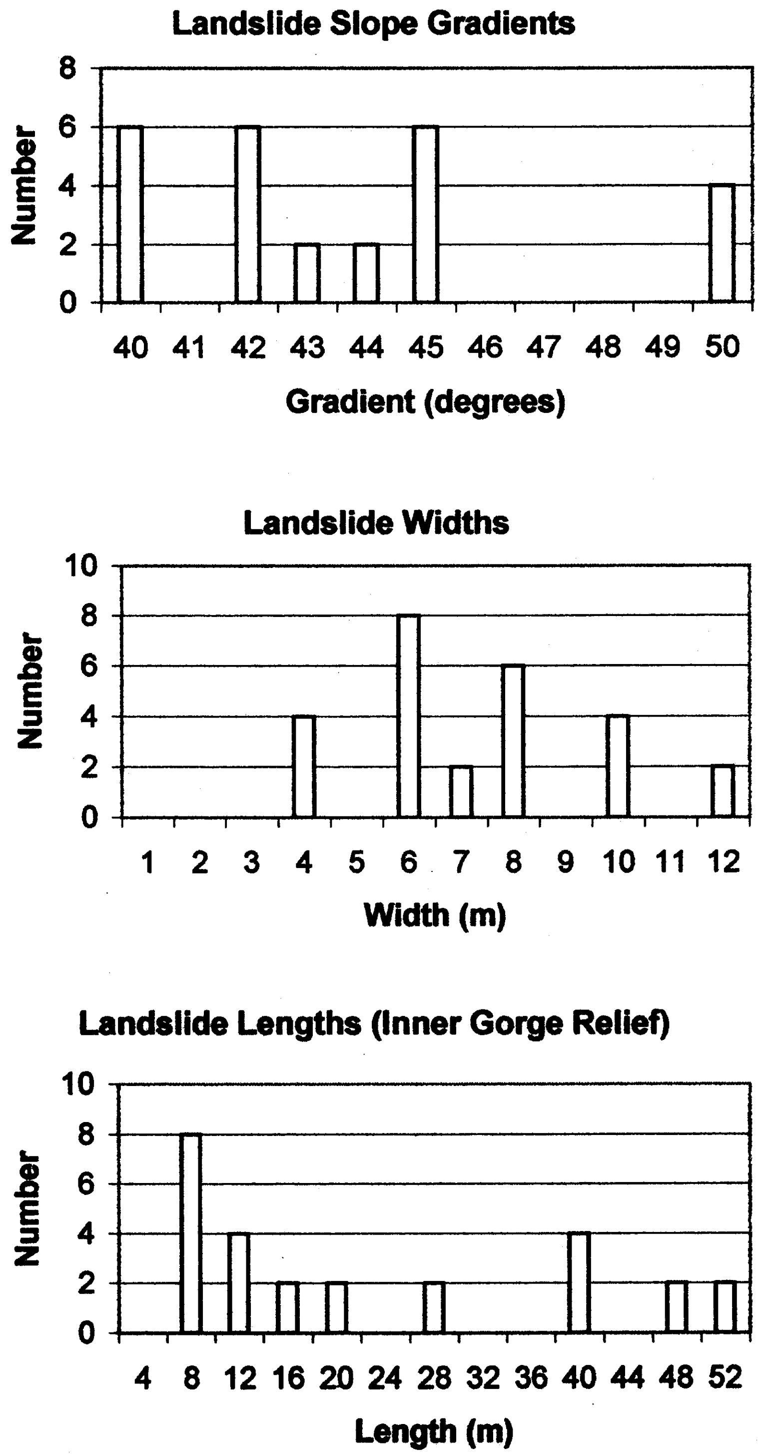

Figure 3-6. Distributions of hillslope gradients, widths, and lengths of shallow landslides located in inner gorges in the Acme WAU. Measurements of landslide lengths are approximately equivalent to the height of the inner gorge landform.

greater than 40 degrees (n = 23). Dragovich and Brunengo (1994) in southwest Washington (in an area of similar landslide processes) estimated that 86% of slides were associated with slopes greater than 36 degrees. Shallow landsliding becomes more probable on slopes greater than 36° because shallow soils (1-2 m, 3-6 ft.) can easily become saturated during intense precipitation when slope angle exceeds the friction angle of the soil (commonly 35°). Although landsliding occurs on lower gradient slopes, the spatial and temporal frequency of sliding would be less.

3.3.3 Field Survey of Landsliding in Close Proximity to Streams: Defining the Inner Gorge Landform

Inner gorges are defined as the local hillslope area adjacent to stream channels and valley floors that commonly contain very steep slopes with a high likelihood of delivery of sediment and wood in the event of landsliding. Numerous landslides were detected in close proximity to stream channels during the inventory using aerial photography. However, hillslope gradients associated with sliding could only be estimated because inner gorge landforms are not resolvable on 1:24,000-scale topographic maps. A field survey was conducted to define the slope gradients associated with landsliding in areas in close proximity to stream channels, and hence to define the physical characteristics of inner gorges in the sandstone basins of the Acme WAU (survey conducted in 1998). The field team consisted of Lee Benda (the mass wasting analyst), Dave Chamberlain (Crown Pacific), Tom Smith (Washington Department of Natural Resources), and Alan Soicher (River Farm Trust). A total of 26 shallow landslides located in inner gorges were visited during the field trips. At each site, measurements of slope gradient, scar width, and landslide length were made. Results are plotted in Figure 3-6. Slope gradients of landslides ranged from 40° (84%) to 50° (119%) and averaged 44° (96%). Landslide scar widths range from 4 m to 12 m (13 ft to 40 ft) and averaged 7.3 m (24 ft). Length of recent landslide scars (soil exposed), which was in many cases analogous to the slope length of the inner gorge, ranged between 8 m (26 ft) to 52 m (170 ft) and averaged 22 m (72 ft). The measured widths are similar to those measured by Buchanan (1988) of 4 to 10 m (12 to 33 ft). Approximately 75% of the slides occurred in hollows with the remaining 25% located on planar slopes.

There are typically several slope breaks encountered as one approaches stream channels in the Acme WAU. The minimum slope break where all of the inventoried landslides occurred, including shallow slides on planar slopes, was approximately 40° (84%). Commonly, the slope break was higher, approaching 50° (119%). In addition, large bedrock hollows often extended uphill of the most landslide-prone break of 40°. These bedrock hollows typically were characterized by hillslope gradients in excess of 36° (73%).

A description of inner gorges is proposed based on the field analysis of landsliding. Inner gorges along second- and higher-order streams are defined as the first slope break greater than 40° (>84%) that is encountered moving away from the stream channel (e.g., 40° below the break with less steep slopes above). Limited field surveys suggest that the slope length of this inner gorge ranges between 8 m (26 ft) to 52 m (170 ft) and averages about 22 m (72 ft). Bedrock hollows that extend upslope from the 40° break in slope (i.e., upslope of the inner gorge, as defined), and that are greater than or equal to 36° (73%) will continue to be considered as a separate landslide prone landform. In addition to old (revegetated) or recent landslide scars which would provide evidence for failure on non-convergent slopes, "discontinuity surfaces" and "wedges" could be used as a field indicator of potential instability. In a study of landsliding on the Chuckanut sandstone formation, Buchanan (1988) identified the landslide potential of discontinuity surfaces, defined as steep, planar sandstone surfaces (containing no fissures or fractures and therefore not penetrated by tree roots). In most cases, discontinuities involve bedding surfaces that dip downslope but they can also be exfoliation joints in massive sandstone beds (Buchanan, 1988). In the field, discontinuities are identified by abrupt and steep temporary breaks in slope, characterized by thin soil or soil-free bedrock areas. Landslide debris (hummocky ground) may be located below the break in slope; this may indicate a low delivery potential. Buchanan also identified failure potential of wedges, which are small pockets of soil located in shallow convergent areas often located at heads of first-order or type 5 streams.

3.3.4 Deep-seated Landsliding

Several areas of deep-seated landsliding in the Acme WAU were inventoried. Each of the areas may contain smaller discrete slide areas within. The first area is an apparently ancient deep-seated landslide/rockfall that is located just north of Devil's Slide and may have formed the small lakes just north of Williams Lake (Section 4). This large slide area may be associated with the bedrock slab failures in the Devil's Slide. Another deep-seated landslide area is centered in the Jones Creek basin and was identified by a convexity or bulge in the longitudinal profile of Jones Creek (see Channel Assessment) and by transverse hummocky topography in Sections 7 and 12. This area contains numerous smaller deep-seated slides within (Figure 3-2). Thorson (1992) mapped several deep-seated landslides adjacent to Jones Creek and these are included in the landslide inventory (Table 3-1; Figure 3-2). There may be other deep-seated landslides scattered throughout the southwest portion of the WAU in the vicinity of Jones and McCarty Creeks and these can be identified during field use of the slope stability maps or during harvest or road layout.

Although some deep-seated landslides were undoubtedly not mapped because they are presently dormant and therefore couldn't be detected under forest canopy by aerial photography, the steep toeslopes (i.e. inner gorges) commonly associated with deep-seated slides may have shallow-rapid landslides that were inventoried if they were visible on aerial photography. The shallow landsliding associated with the toeslopes of dormant deep-seated landslides is accounted for in the landslide-prone inner gorge landform.

3.3.5 Analysis of Sediment Delivery

Sediment delivery to stream channels of various orders by mass wasting was also inventoried from aerial photographs and during field surveys. Of particular interest is whether debris flows can impact channels containing fish habitat. The majority of slides occurred within bedrock hollows and inner gorges and they deposited in fish-bearing, third- through higher-order streams. Long-runout debris flows (debris flows that initiate at the heads of first-order channels and then travel through first- and second-order valleys) have occurred numerous times in the west-side tributaries including Potter, Sygitowicz, Standard, Falls, McCarty, and Jones Creeks (Table 3-1; Figure 3-2). In Table 3-1 (DNR Form A-1), debris flows, by definition, entered at least a type 5 stream (e.g., first-order). Hence, type 5 streams are not included in Table 3-1. Many of these failures undoubtedly triggered dam-break floods that exited the mouths of basins impacting fans although they were categorized as debris flows. Debris flows on the east side of the South Fork Nooksack River have been confined to convergent areas near the Devil's Slide. The majority of the landslides inventoried from the 21 year aerial photo record delivered sediment to stream channels of third- and higher-order (Table 3-1) The proportion of all landslides that delivered sediment directly to third- and higher-order channels ranged from 50% to 74% in photo years 1970, 1978, 1983, 1991, and 1995.

Landslides and debris flows may also deliver sediment and woody debris directly to public works, such as highways and county bridges, and to occupied fans. Vulnerability to public works for the purpose of creating rule calls is included in watershed analysis. Debris flows and dam-break floods also pose a serious threat to private property and human life. Vulnerability of occupied fans to sediment-related hazards from mass wasting is not included in watershed analysis, and hence formal rule calls that deal specifically with private property were not made. Rather, the analysis team recommends that when private residences exist downstream from landslide-prone areas, further voluntary management prescriptions be considered (see Prescriptions). Potential hazard areas on fans (due to debris flows and dam-break floods) were not mapped as part of this analysis. Some alluvial and debris flow fan hazard areas have been identified by Whatcom County (Caplow et al., 1992). Potentially hazardous areas of the Jones Creek fan have also been delineated by Raines et al. (1996). In general, all of the tributary basins (including type 4 and 5, or first- and second-order streams) that contain landslide prone areas have fan hazard areas at their mouths, and the assessment of the hazard for each tributary should be done on a site specific basis.

A landslide hazard exists when there is a relatively high potential for delivery of sediment (and wood) to important resources, including streams and engineered structures. At times in the field, the ability of a landslide site to impact a resource will need to be determined (see Prescriptions). Models exist for predicting landslide runout or delivery in channelized environments (Benda and Cundy, 1990). The analyst is not aware of a method for predicting runout and deposition of non-convergent slopes. To fill this need, a method for predicting landslide runout on non-convergent hillslopes was developed and is presented in Appendix 3-1 (this model is presently being tested in conjunction with the Oregon Department of Forestry).

3.4 SLOPE STABILITY MAP UNITS

Ten mass wasting map units were developed for the Acme WAU for the purpose of differentiating among areas in the watershed having different landslide processes, natural susceptibilities to failures, sensitivities to forest practices, and delivery of sediment to streams or engineered structures. The ten mass wasting map units are described in Table 3-3 and on DNR Form A-2 (located in Appendix 3-2) and mapped in Figure 3-7 (DNR Map A-2). The slope stability map of Thorsen and others (1992) for the Jones Creek area was consulted, and the slope stability map (Figure 3-7) is consistent with the Thorsen map. In addition, information on location of unstable areas in R4E T38N, Section 25 and R5E T38N, Section 30 was obtained from River Farm, Evergreen Land Trust (O'Neil, 1996) and used in the development of slope stability and hazard maps.

Shallow landsliding and debris flows (and dam-break floods triggered by these processes) are the most significant mass wasting processes in the Acme WAU and represent the largest threats to fish habitats, public works, and private property. In general, convergent areas (bedrock hollows, swales, channel heads) that are steeper than approximately 36 degrees has the highest likelihood of failure (Figure 3-5). This finding is consistent with landslide inventories contained in Syverson (1984) and Buchanan (1988) and discussed in Benda (1989). In the Acme area, landsliding can occur on slopes less than 36 degrees, although landslide frequency is much less compared to steeper slopes. Non-convergent slopes are also susceptible to failure although failure probability increases with increasing hillslope gradients. Buchanan (1988) analyzed two planar failures which he referred to as "discontinuity failures" that occurred on hillslopes of 34 - 29^0 and 43^0. In general, planar failures that do not enter steep and confined low-order streams should have a low likelihood of delivery.

Based on an inventory of 26 shallow landslides in inner gorges in the sandstone terrain of the Acme WAU, a 40 degree cutoff is chosen to represent the highest landslide-prone area (planar and divergent slopes) in inner gorges. The 40 degree cutoff does not include bedrock hollows located in inner gorges. Bedrock hollows located in inner gorges are defined by a slope gradient> =36°. When landslides are observed on planar or divergent slope forms, the slope gradient of the landslide head scarp should be used to define nearby hillslope gradients that are at risk from landsliding. Furthermore, the 40 degree slope gradient cutoff may not apply to the weaker rocks of the phyllite formation location predominantly in the Jones Creek area. Hence, in the phyllite terrain in the Acme WAU, field evidence of shallow landsliding, small rotational slumps, tension cracks, and tipped and deformed trees should be

Table 3-3 A summary of slope stability map unit descriptions for the Acme WAU. (See DNR form A-2 for further details.)

MWMU #1: Initiation sites of shallow landslides and debris flows. Debris deposits may trigger dam-break floods. Map unit is defined as convergent topography (bedrock hollows) of slope gradient >=36 degrees and generally first-order inner gorges. Area may also contain more shallow bedrock depressions, referred to as wedges (see text). Delivery to fish-bearing channels and/or occupied fans. Map unit #1 is a variable-width zone (see prescriptions). The unstable zone may be locally wider or narrower for short distances depending on local topography.

MWMU #2: Initiation sites of shallow landslides and debris flows. Debris deposits may trigger dam-break floods. Unit is defined as inner gorges of second- through higher-order channels with landslide-prone planar and divergent slopes having gradients in excess of 40°. Hollows in close proximity to stream channels, although located in inner gorges, are defined by a slope gradient threshold of >=36° similar to map unit #1. The map unit contains all slope forms with convergent and planar being the most potentially unstable. Delivery to fish-bearing channels and/or occupied alluvial/debris fans, particularly by dam-break floods.

MWMU #3: Initiation sites of shallow landslides and debris flows. Debris deposits may trigger dam-break floods. Predominantly non-convergent hillslopes greater than or equal to 31 degrees of all slope forms. Map unit contains numerous unmapped convergent areas which should be steeper than surrounding planar slopes (i.e., MWMU #1). Delivery to fish-bearing channels and/or occupied alluvial/debris fans. Convergent areas between 31 and 35 degrees are susceptible to failure but at a lower rate compared to hollows >=36 degrees. Planar slopes >=40 degrees are also susceptible to failure but less than convergent areas. Planar, 36 - 40 degree slopes have a lower likelihood of failure compared to steeper areas. Broadly mapped as two areas: map unit 3A contains predominantly >=36^0 slopes (including hollows) and map unit 3B contains 31 to 35^0 slopes (including hollows). Map unit requires field identification of slope gradients and slope forms.

MWMU #4: Same as map unit #2 but long runout debris flows through fish-bearing waters do not occur. Landslide-derived sediments is transported into fish-bearing reaches by fluvial processes.

MWMU #5: Same as map unit #1 but long runout debris flows through fish-bearing waters do not occur. Landslide-derived sediments is transported into fish-bearing reaches by fluvial processes.

MWMU #6: Devils slide area. Failures of bedrock slabs. Delivery to base of cliffs. Broadly mapped as one unit and landforms and delivery need to be determined in the field on a site specific basis. Map unit may extend into MWMU #7. Individual

Table 3-3 cont.

bedrock fractures and detached slabs not inventoried. Slope gradients >= 30 degrees and all slope forms. Probably contains other map units.

MWMU #7: Shallow landslides and small debris flows and possibly bedrock slab failures. General map unit contains areas that range from approximately 30 degrees to greater than 40 degrees and contains all slope forms including numerous unmapped bedrock hollows and small inner gorges. May also contain a part of the Devils slide area (map unit #6). Unit also contains stable areas such as ridges and lower gradient landforms. Broadly mapped as one unit: landform and delivery need to be determined in the field on a site specific basis. Canopy cover precluded mapping of individual landslide areas. Map unit #7 contains the map units 1, 2, and 6.

MWMU #8: Landslide activity is rare to non existent, and/or no landslide delivery directly to streams of any order. Includes landforms such as hillslopes, valley floors, and ridges. Slope gradients less than or equal to 30 degrees. May contain small, localized deep-seated/earthflow areas, located primarily south of McCarty Cr. basin. Inclusions of less stable areas need to be identified with site specific field surveys. Area contains steeper, more unstable ground but that do not deliver to any water or other public resources.

MWMU #9: Active and dormant deep-seated landslide terrain. Sliding along rotational failure planes but shallow landsliding along over-steepened toes is likely. Failures into Jones Creek may trigger dam-break floods. Dormant areas characterized by hummocky topography and evidence of past failures. In some cases, tipped and deformed trees and small tension cracks (centimeters) indicate slow deformation. Active areas characterized by large ground ruptures (meters) and recent displacement of soil blocks or groups of blocks. In addition, active failures may be recognized by fresh slide scarps and downed trees Slope gradients generally greater than 20 degrees. Landslides generally most active near toes along channels and immediately upslope. Deep-seated landslides may also be located in map unit 2 in the Jones Creek basin, and in some cases they are unmapped. The deep-seated landslides may be the largest sediment source for the Jones Creek fan. High sediment delivery ratio.

MWMU #10: Shallow landsliding and debris flows, and to a lesser extent small, sporadic deep-seated failures. Landsliding is generally uncommon in this unit, although the possibility exists for failure. Slope gradients generally between 31 and 35 degrees. The unit may contain unmapped inclusions of map unit #1 but this should not be common. Mostly planar topography with some broadly convergent areas.

landsliding, the 40 degree cutoff should be applied. In his analysis of landsliding mechanics in the Smith Creek drainage, Buchanan (1988) estimated the minimum slope gradient necessary for failure for various vegetation types. For "mixed forest" and "understory" interpreted here respectively as second- growth forest and clearcut, the limiting slope gradients were 30 and 25 degrees. These estimates are supported by field inventories of landsliding which shows failures on slopes as low as 25 - 30 degrees. However, all stability analyses (this one, [Figure 3-1 and 3-7] Syverson (1984) and Buchanan (1988)) show that the majority of landsliding occurs on slopes in excess of approximately 36°. This assessment indicates that approximately 90% of shallow slides in the sandstone terrain occurs in slopes in excess of 35° (72%).

The number of landslides in each map unit over the 21 year period of record is plotted in Figure 3-8. Comparing Figure 3-8 with the size (aerial extent) of each map unit in Figure 3-7 can be used to roughly estimate landslide spatial frequencies and hence the relative susceptibilities of each map unit to landsliding (and the sensitivity of each map unit to forestry activities, see below). Based on this, the map units most naturally susceptible to landsliding in order of importance include 1, 2, 3, and 6. Refer to Table 3-3 and Appendix 3-2 for a complete description of map units.

Four of the map units are broadly defined because it was not practicable to differentiate among variations in slope gradient and slope form either from aerial photographs (1:12,000 scale) or topographic maps (1:24,000-scale). These include map unit #2 which consists of inner gorges that contain bedrock hollows, and planar and divergent slopes of greater than 40°. Map unit #2 may also contain lower-gradient topography but in general these areas are less or not prone to shallow landsliding. Although map unit #2 may contain small, localized, deep-seated landslide terrain, these areas cannot be mapped remotely and must be identified during field use of the slope stability map.

Map unit #3 contains a mixture of predominantly non-convergent topography with slopes greater than 31 degrees. The steeper areas of map unit #3 may contain a high density of unmapped hollows of either >= 36 degrees (i.e., map unit #1, see Table 3-3) or hollows of between 31 and 35 degrees. Map unit #3 is broadly mapped as two areas: map unit 3A contains predominantly >=36° slopes (including hollows) and map unit 3B contains 31 to 35° slopes (including hollows).

Map unit #7 contains areas between 30 and 40 degrees (with some local areas steeper). The map unit contains numerous bedrock hollows (>= 36°) and inner gorges of first-order channels (i.e., map unit #1) in addition to parts of the Devil's Slide (map unit #6). Map unit 7 also encompasses large areas that are much more stable (ridges and lower gradient areas).

Some of the map units contain unmapped inclusions of topographies that are different that what is defined in the units. This arises because of the dependence of slope stability mapping predominantly on remote sensing (i.e., topographic maps and aerial

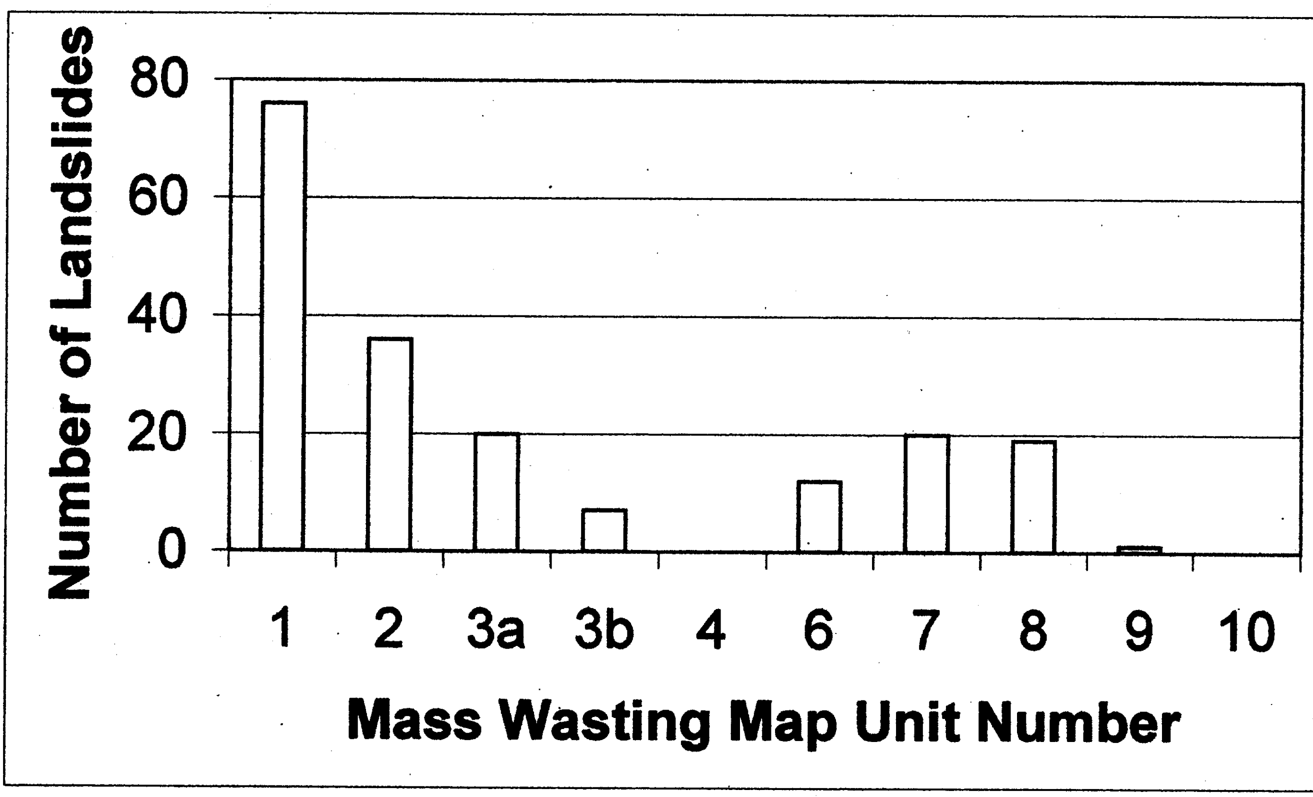

Figure 3-8 Total number of landslides in each of the ten mass wasting map units.

photographs). The issues of map accuracy and on identifying unmapped inclusions are discussed in Section 3.8 and in the prescriptions.

It is important that the slope stability map units developed during this analysis encompass the landslides that have occurred during the last 20 years, particularly large slides that have delivered sediment directly to fish-bearing streams and to occupied fans. Partly, this is a check on whether map units are sufficiently detailed to accurately distinguish between stable and unstable areas. To determine this, landslides and debris flows, with and without direct delivery into fish-bearing channels in the Acme WAU, are categorized according to the ten map units in Figure 3-8. The majority of landslides and debris flows that deliver sediment directly to fish-bearing channels or fans (~88%) are captured in the most unstable map units of #1, #2, and #3. Summary statistics for each map unit regarding landuse and type of mass wasting are shown in DNR Form A-3 of Appendix 3-3.

3.5 SENSITIVITY OF MASS WASTING MAP UNITS TO FORESTRY ACTIVITIES

Forestry harvest activities can contribute to slope instability. The loss of tree root strength following timber harvest may accelerate sliding in recent clearcuts (generally less than 20 years old). Increased saturation of the soil may occur in road prisms, or immediately below roads because of road drainage capture and diversion, and because of rain-on-snow increases in soil moisture in clearcuts. Some of these effects of logging on certain naturally unstable landforms are well documented in the literature (Sidle et al., 1985; Benda et al., 1991). In addition, removal of material from toes of dormant, deep-seated landslides during road construction and maintenance can lead to reactivation of deep-seated landsliding.

During the landslide inventory, occurrences of mass wasting were associated with land use activities, including clearcuts (less than approximately 10 years old based on loss of tree root strength), young forests (between approximately 10 and 30 yrs old based on reestablishment of root strength), mature forests (greater than approximately 30 yrs old), and logging roads (Table 3-3). Approximate ages of forests were estimated from aerial photography. There were more slides associated with logging roads than clearcuts in the Acme WAU (Figure 3-9), which is consistent with other studies that have shown roads to be the dominant trigger of landsliding in managed forests. Overall, 32% of the slides (all types) were associated with clearcuts, 45% with logging roads (mostly active), and 16% with mature forests (predominantly inner gorge landslides). An additional three percent occurred in young forest and 4% of slides were not associated with land uses (i.e., never harvested). For slides in clearcuts it is not possible to accurately differentiate between loss of root strength and increased soil saturation due to rain-on-snow. Buchanan (1988) estimated that rain-on-snow can be a significant factor in triggering shallow landsliding on terrain nearby to the Acme WAU. In general, because failures often occur during the period of lowest root strength (Sidle et al., 1985), rain-on-snow is assumed to be a second-order or less important effect. However, the sensitivity of

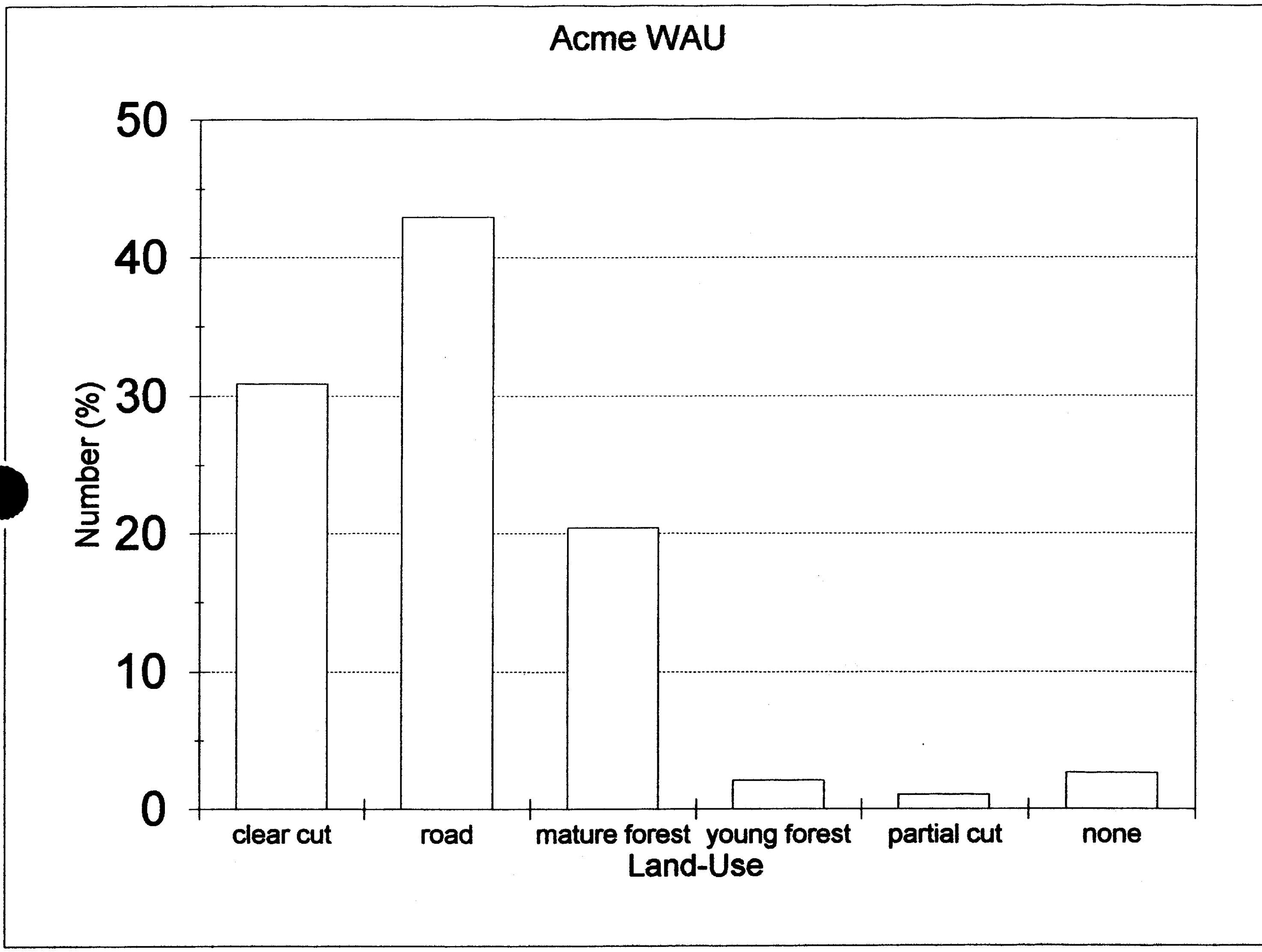

Figure 3-9 Number of landslides associated with various forestry activities and forest types.

map units to forestry activities (discussed below) assumes that both loss of root strength and rain-on-snow increases in subsurface flow are contributing factors to failures, but these effects are not differentiated.

During the January, 1983 storm many failures were initiated in second-growth forests (mixed conifer and hardwoods), particularly in basins just west of the Acme WAU (Syverson, 1984). Buchanan (1988) during his analysis of landsliding estimated that root strength for these "mixed forests" was less than what would be expected for mature old growth forests.

Landslide frequency can be used as a means to estimate the sensitivity of map units to forestry activities. Based on visually comparing Figure 3-8 with the size of the individual map units in Figure 3-7 indicates that the relative sensitivities of map units to forestry activities are 1 > 2 > 3 > 6 > 9 > 10 > 8 (map unit #7 is a undifferentiated mixture of those units but as a whole would probably fall between either 1 and 2, or 2 and 3.) Hence, bedrock hollows, heads of first-order channels, and inner gorges of channels of all orders with hillslope gradients greater than or equal to 36 degrees - contained in map units #1, 2, 3, 6 and 7 - are the most sensitive to forestry activities, both clearcuts and logging roads. Bedrock hollows of a lower gradient (i.e., 31 to 35 degrees) are also sensitive to forestry activities but to a lesser degree compared to the hollows of > =36 degrees. These lower gradient slopes are probably more sensitive to logging road related problems, such as drainage diversion and road fill failure. There is not a threshold slope gradient above which landslides occur. Rather, the probability of failure steadily increases with increasing gradient, although the rate of increase in probability increases at higher slopes. The slope break at 36 degrees chosen here denotes the approximate gradient at which, it is surmised, the rates of increase in landsliding change based on the landslide inventory, other inventories in the region, and on theoretical considerations of shallow landsliding.

The sensitivity of map unit #6 (large bedrock slab failures) to forestry activities cannot be determined empirically because of the lack of clearcut activity coinciding with available aerial photographs. From a theoretical perspective, timber harvest should not affect the stability of the Devil's Slide, since the sliding mechanism involves large tensional forces in bedrock (i.e. mountain splitting) that should be little effected by rooting strength. Road construction, however, involving blasting and removal of bedrock, could change the distribution of forces in the bedrock and therefore further weaken areas of the Devil's slide. An analytical analysis could be conducted that would better quantity the effects of forestry activities on the Devil's Slide.

It is also not certain to what extent forestry activities affect the stability of the deep-seated landslide centered in Jones Creek (map unit #9). In one instance, a ground rupture along the perimeter of an existing slide scarp was detected in this landform in a clearcut (1991 photo), but it is uncertain to what extent harvest was involved in the slide reactivation. In addition, sediment mobility and delivery would have to be considered on a site specific basis to define a hazard for such slides. The area in the deep-seated slide with the highest potential to be affected by forestry activities is the inner gorge (map unit #2 - already designated as highly sensitive to forestry activities, see above).

There are small, localized, unmapped deep-seated slides located either in map unit #9 or #8. The sensitivity of these slides to forestry activities is also unknown, although aerial photography does not show reactivation of or new small, deep-seated failures following timber harvest in these areas. Again, sediment mobility and delivery would have to be considered on a site specific basis to define the hazard ratings for such slides.

Another effect of forestry practices is the removal of streamside forests along channels of any order. The susceptibility of first- and second-order channels to debris flows, and higher-order channels to dam-break floods is increased by the removal of large streamside forests and its replacement with small, second growth conifers and alders. This is because large trees inhibit the propagation of some mobile mass movements when intercepted early (Coho and Burges, 1993).

Although several of the mass wasting map units identify convergent areas (bedrock hollows) as prone to landsliding, only a portion of any bedrock hollow is involved with failure. Generally, shallow landslides in hollows occur some distance below ridgetops or hillslope crests and the scars are fairly narrow. The areas within and immediately adjacent to a landslide scar provide the critical root strength. The widths (at headscarps) and distances downslope from ridgetops of five landslide scars located in convergent areas in the Smith Creek basin (just west of the Acme WAU) were measured by Buchanan (1988). The scar widths ranged between 4 and 10 m (13 - 33 ft) and averaged 6 m (20 feet) Similar measurements were obtained from landslides examined in the field during this study (see Table 3-2). The distances from ridgetops to the tops of the landslide scars ranged between 20 and 260 m (66 - 850 feet) and averaged 60 m (200 feet). See also Benda et al. (1998) for guidance in determining the most unstable portion of bedrock hollows.

3.6 HAZARDS ASSOCIATED WITH MASS WASTING MAP UNITS

Hazards associated with mass wasting map units depend on: 1) the mass wasting process (e.g., small landslide versus large debris flow or dam-break flood); 2) the spatial density or failure frequency; 3) the ability of sediment to be delivered to streams with sufficient volume onsite or offsite (by fluvial transport) to pose an adverse effect on fish and other aquatic resources; and 4) the sensitivity of the map unit to forestry activities. The design of watershed analysis calls for a three-tiered approach to the setting of hazards: high, moderate and low (refer to the manual for the development of hazard calls). In general, the highest hazard pertains to the highest frequency of sliding in combination with the greatest potential impacts to resources. Low hazards apply to areas where landsliding is rare to non existent or to areas that do not deliver to resources. As a consequence, a moderate hazard contains a potential for landsliding and delivery of sediment (and wood) to resources but landsliding occurs at a lower spatial frequency compared to high hazard areas. The hazard ratings were developed during discussions with other members of the watershed analysis team during synthesis meetings. The potential hazards associated with each of the ten map units are shown on the hazard map (Figure 3-10 (DNR Map A-2)).

Resource vulnerability ratings, typically applied to fish habitat and public works in formal watershed analysis, are not routinely applied ot private property. However, because the watershed assessment team recognizes the potential vulnerabilities of private residences to debris flows or dam-break floods, the issue of hazards to private property is taken up in the prescription section.

The hazard ratings are discussed below.

Map unit #1 is a high hazard because of the combination of unstable landforms (i.e., > =36 degree convergent areas), high potential for sediment delivery to streams, public works or occupied fans, and a high sensitivity to forestry activities.

Map unit #2 is a high hazard because of the natural susceptibility of landslides, its sensitivity to forestry activities, and the delivery of sediment directly to lower gradient streams with fish and public works. This applies to > =36 degrees convergent slopes and > = 40° non convergent slopes with a potential to deliver sediment and debris to stream channels. Convergent areas with slopes of 31 to 35 degrees are considered a moderate hazard.

Map unit #3 is rated as a high *or* moderate hazard. Non-convergent hillslopes between 31 and 39 degrees are considered moderate hazards. Map unit #3 contains unmapped inclusions of map unit #1 and areas where this is a high likelihood are mapped broadly as a high hazard. Hollows between 31 and 35 degrees are moderate hazards. Non-convergent hillslopes >40° are a high hazard only if there is a high likelihood of delivery sediment to streams (use runout models, either Benda and Cundy, 1990 for channelized situations or the method in Appendix 3-1 for non-convergent areas. Map unit #3 is broadly mapped as two areas with two different hazard ratings: map unit 3A contains predominantly > =36^0 slopes (including hollows) and is ranked as a high hazard and map unit 3B contains 31 to 35^0 slopes (including hollows) and is ranked as a moderate hazard. Moderate hazard hollows are likely most susceptible to road related problems.

Map unit #4 is ranked as a moderate hazard because landslides within the inner gorge should be of low volume and not trigger dam-break floods.

Map unit #5 is ranked as a moderate hazard because the deposition of sediment and woody debris is upstream of fish-bearing waters and sediment would be transported downstream to fish-bearing waters by fluvial processes. Although map unit #5 is not on the map of mass wasting units, it is included because such areas will likely be found during field surveys.

Map unit #6 with delivery to public works and streams is a high hazard with respect to road construction (all slope gradients and slope forms), and a moderate hazard with respect to timber harvest alone (see Section 3.5); with no delivery to waters it is a low hazard. An analytical analysis of deep-seated bedrock landsliding could change the hazard ratings.

Map unit #7 is conditionally ranked as a high hazard because it contains map units #1, #2, #3, and possibly #6 (with delivery), and these areas are unmapped because forest canopy precluded their identification using aerial photography. The location of landslide prone areas need to be determined in the field. Map unit #7 contains inclusions of more stable landforms (moderate and low hazards areas) which need to be located in the field.

Map unit #8 is ranked as a low hazard either because there is no direct sediment delivery to channels of any order, or because landforms have limited landsliding because of low gradients.

Map unit #9 Individual deep-seated landslides that show signs of being recently active and that deliver sediment to public works or streams is ranked as a high hazard. Other deep-seated slide areas that appear to have been dormant for periods of many decades to centuries are ranked as low with respect to timber harvest alone, and a high hazard with respect to road construction where blasting or large removal of sediment on the slide area is anticipated.

Map unit #10 is ranked as a moderate hazard because of a relatively low frequency of landsliding.

The volume of a debris flow after it passes through first- or second-order channels is strongly controlled by the rate of erosion of sediment and wood from within those channels (Benda and Cundy, 1990). Hence, the volume of sediment and wood transported by debris flows is controlled by the time since the last debris flow. Likewise, the volume of woody debris that accumulates in higher-order channels which can affect the volume (and destructiveness) of a dam-break flood (often referred to as a debris torrent) is also controlled by the time since the last dam-break flood and by the rate of debris production. Therefore, bedrock hollows that have had recent failures, and first- through higher-order channels that have had recent debris flows or dam-break floods may pose a much lower hazard compared to those sites prior to failures. This also applies to larger mountain tributaries susceptible to dam-break floods.

3.7 CONFIDENCE IN ANALYSIS

The Level 2 mass wasting analysis is considered to have a high degree of confidence with respect to identifying unstable landforms because of the following reasons:

1) the extent of the aerial photograph coverage that allowed for an investigation of mass wasting processes over a period of 20 years (photo years: 1970, 1978, 1983, 1987, 1991 and 1995);

2) the field assessment that allowed for identification of landsliding and associated hillslope characteristics; and

3) other slope stability studies in the area including Easterbrook (1983), Syverson (1984), Buchanan (1988), Thorson (1992), and Raines et al. (1996).

3.8 LIMITATIONS AND APPLICATION OF ASSESSMENT

3.8.1 Uncertainty

This slope stability assessment, which is based on the methodology of Watershed Analysis (WFPB, 1994), uses up-to-date scientific information on landsliding and the effects of forestry activities on landslide initiation. Hence, it is likely that all major types of landsliding and their associated landforms have been described during this analysis. In some cases, areas of potential landslide hazard may not always be identified because of: 1) the dependence on remote-sensed data (i.e. aerial photographs); 2) the unique 30-year history of storms that triggered the landslides used to create the mass wasting map units (i.e., longer and different time periods and larger storms than what occurred during the aerial photo record may yield landslides in areas previously mapped as stable); and 3) the incomplete scientific understanding of all landslide mechanisms. For all of the reasons above, the mass wasting map units and hazard units may not completely identify all of the potentially unstable areas in all cases.

3.8.2 Map Accuracy

The slope stability mapping units describe general physiographic areas each having distinct landforms and mass movement processes and potential. The boundaries between mapping units are approximate. This is for two reasons. First, only a small percentage of the study area was actually observed and field mapped during the field surveys. Areas not observed in the field were mapped using stereographic pairs of aerial photographs and topographic maps. Second, in many areas it is not possible to locate accurately the position of certain landform boundaries on topographic maps, or on aerial photographs particularly under forest canopy. Therefore, actual boundaries between mapping units in any specific location in the study area need to be verified (and possibly corrected) during the field use of the slope stability map for purposes of harvest unit layout and road design, and layout by foresters or road engineers. For example, often bedrock hollows and inner gorges are not recognizable on 1,24000-scale topographic maps or on 1:12,000-scale aerial photographs of forest canopy. Generally, the extent and exact location of bedrock hollows and inner gorges must be determined in the field. The dependence of mapping on aerial photography and topographic maps limits the ability to locate and map all small-scale topographic features relevant to landsliding. Hence, the slope stability maps should always be used in conjunction with field observations to improve the accuracy of the slope stability map.

3.8.3 Field Application of the Slope Stability Assessment

The slope stability and hazard maps are to be used as a general guide to the types and location of potentially unstable areas. The boundaries between units need to be determined in the field. The scale of mapping (e.g., 1:24,000) ensures that there will be unmapped inclusions of unstable areas in mapped stable areas and vica-versa. Hence, field visits are critical for the application of the slope stability maps. Refer to the prescriptions regarding the procedures appropriate for identifying unmapped inclusions.

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APPENDIX 3-1

Appendix 3-1: Method to Predict Landslide Runout on Non-Convergent Hillslopes

by
Lee Benda Ph.D.

Background

The degree to which landsliding is considered an environmental impact depends in large part on the delivery of landslide debris to stream channels. Many factors govern the travel distance, or runout, of landslide debris including landslide volume, topography over which landslides travel (slope gradient, slope form, roughness etc.), debris thickness, water content, and the grain size distribution of the debris. Following failure, landslides typically liquefy as the saturated soil mass and its reinforcing network of roots break up. When landslide debris enter and flow within small, steep stream channels they are referred to as debris flows. Debris flows typically contain 70 to 80% soil and only 20 to 30% water. Erosion of additional sediment and organic debris in small and steep channels can increase the volume of the original landslide by 1000% or more (Benda and Cundy, 1990). Debris flows in channels can runout thousands of meters on relatively low-gradient slopes (5 – 20%), in part, because the confined nature of channels results in increased flow thickness which enhances runout and prevents deposition. Methods for predicting the approximate location of debris flow runout in confined mountain channels has been developed (Benda and Cundy, 1990; Fannin and Rollerson, 1993). Such methods could also be combined with models that consider runout of debris on fans due to momentum (Takahashi and Yoshida, 1979).

Runout of landslide debris can also occur over non-convergent slopes. In general, less is known about this form of landslide runout compared to channelized debris flows. Some sediment delivery rules have been proposed for specific geographic areas where field observations on runout characteristics were available (Collins et al., 1994; Forest Practices Code of British Columbia). However, the lack of testing limits the extrapolation of these methods to other areas.

Sediment Delivery Model for Non-Convergent Hillslopes

A sediment delivery model for non-convergent hillslopes is described below (e.g., non channelized landslides). The model is based on the theoretical principle and empirical finding that moving landslide debris contains a relatively rigid (non shearing) raft, or plug, of debris on the surface, a rheology referred to as coulomb-viscous (Johnson, 1984). Semi-liquefied landslide debris that moves downslope, and which does not continue to trigger additional landslides beneath the moving debris (see later), will spread, thin, and deposit. Landslide debris should stop moving when the debris has thinned to a point where it equals the thickness of the non-shearing rigid layer. Thickness of the landslide debris at deposition, referred to as its critical thickness, is governed by the shear stress in the debris and the resistance of the debris to shear, the latter property referred to as a yield strength (Johnson, 1984). With a varying shear stress within the landslide debris caused by gravity on an inclined surface and a constant yield strength, the critical thickness will vary with hillslope gradient and increase with decreasing gradient.

A series of environmental factors govern the runout of landslide debris using the coulomb-viscous model including the initial volume of the landslide, the moisture content of the debris expressed as the unit weight of material (kg/m^3 multiplied by acceleration of gravity), the slope of the hillslope over which the debris is moving, the yield strength of the debris, and roughness of the slope (standing trees, stumps etc.,). The latter factor is ignored in the present analysis, although increased roughness should lead to shorter travel distances. The yield strength of the debris is dependent on many site specific factors, including grain size distribution, percent of silt and clay, and moisture content (Innes, 1985; Benda, 1988).

Johnson (1970, 1984) derived equations of shear stress and motion for landslide debris (referred to as debris flows) for both confined and wide channels. In wide channels (which would be applicable to a non-convergent hillslope where spreading of the debris would create a geometry of flow with debris thickness is some small fraction of its width), the relationship between yield strength of the debris (K), critical thickness (T_c), hillslope gradient (y), and the unit weight of the material (Q) is given by:

$$T_c = K/(Q \sin(y)) \quad (1)$$

Yield strength of landslide debris can be estimated using (1) by measuring the deposit thickness of landslides (or debris flows) in the field, along with estimates of the unit weight of debris and the slope on which the debris deposited (Johnson, 1984). Thicknesses of landslide deposits in the region are commonly on the order of one to two meters on slopes of three to six degrees (Benda, 1988; unpublished data). Unit weight of liquefied landslide debris (debris flows) has been estimated to be approximately 18000 nt m^{-3} (Benda, 1988). These values should apply in general to many areas in western Washington. Exceptions may include clay-rich landslides originating from glacial deposits and estimates of material properties may change in those cases. Using these values, including a deposit thickness of 1.5 m at a slope of 5 degrees in (1), gives a yield strength of approximately 1500 nt m^{-2}.

According to (1), the critical thickness of the debris (T_c) is dependent on the hillslope gradient. Using the estimate of yield strength of landslide debris of 1500 nt m^{-2} allows the calculation of the dependence of critical thickness on slope angle (Figure 2). The critical depth, or depth of the deposition layer (T_c), varies with hillslope gradient and ranges from less than 0.25m on hillslopes of about 30° (58%) to about 1m on hillslopes of about 5° (9%) (Figure 1). Hence, thickness of deposition will vary along the flow path of a landslide in non-channelized environments (relatively planar hillslopes).

Landslide debris that moves down non-convergent hillslopes spreads laterally unless constrained by objects on the hillslope including micro topography, logs, stumps, standing trees etc. An idealized flow path of landslide debris on non-convergent, or planar topography, is shown in Figure 2. Runout of landslide debris along the flow path is governed by the volume of the landslide, the thickness of the debris during deposition, referred to as the critical thickness, the width of the landslide at the beginning of its runout, and the angle of spread (B in Figure 2). Hence, the relationship between landslide volume and runout length is:

$$V = [(W_oL) + (L^2\sin B)]*T_c \tag{2}$$

where V is the initial landslide volume (additional failure or scour of hillslopes is not covered by this model, see next section below), L is the landslide length or runout, W_o is the initial width of flow or landslide scar width, T_c is the critical deposit thickness (from Figure 1), and B is the spread angle. With a non-varying landslide volume, the runout distance (L), using the idealized flow geometry in Figure 2, can be represented as a quadratic function of landslide volume (V):

$$L(V) = [((T_cW_o)^2 - 4(T_c\sin B(V)))^{1/2} - T_cW_o]/2(T_c\sin B) \tag{3}$$

Equations (2) and (3) assumes that the velocity profile of the moving debris is parabolic with the highest velocity at the surface (Johnson, 1984). Hence, the top layers of the debris would shear and move on top of the basal layer(s). This process of thinning, directly downslope and laterally controlled by the spread angle, would eventually create a layer of debris which would stop moving. The deposit layer would have a thickness governed by the yield strength of the debris in relation to the shear stress, or a critical thickness (Figure 1).

Parameters for use in (3) can be obtained from field studies or landslide inventories. For example, a typical width of a landslide in the Chuckanut formation located in northwestern Washington is about 4 to 8 m and a spread angle of 4.3 degrees has been measured in the same area (Buchanan, 1988). Likewise, a characteristic landslide volume can be obtained from field measurements. Estimates of landslide runout as a function of landslide volume are made using a range of critical thicknesses, 0.25m to 0.75m representing slope angles of 30^0 to 6^0 (Figure 1). Using a W_0 of 8m and a spread angle of 4.3° (from Buchanan, 1988), the predicted landslide runout is plotted in Figure 3. For example, given a landslide volume of about 350 m^3 (455 yd^3), the predicted runout distance ranges between 40 and 80 m (130 to 260 ft) (Figure 3). The range of critical thickness indicates that the runout will be closer to 130 ft on low-gradient areas, such as flat valley floors or fans, and runout will approach the higher value on steeper slopes.

Field estimates of slope length are necessary to compare with predictions of landslide runout and delivery to estimate delivery hazards (see below). Slope length estimates are made on a site specific basis and will reflect various topographies.

Application of the Coulomb-Viscous Landslide Delivery Model

The runout model (Equation 3 and Figure 3), referred to hereafter as the Coulomb-viscous model, requires that the volume of a landslide does not increase during the duration of the runout. Landslides that are triggered within, or runout into, convergent areas, such as debris flows in first- and second-order channels, commonly increase their volumes downstream by scour of channel beds (Benda and Cundy, 1990).

Furthermore, confined headwater channels prevent spreading and landslide debris maintains depths much in excess of critical thicknesses, allowing long runouts.

Steep, non-convergent slopes (e.g., unchannelized) that are near saturation may be meta stable and have a factor of safety near 1. [Factor of safety is the ratio of stabilizing to destabilizing forces on a hillslope. When factor of safety is less than one, failure is predicted.] Landslide debris that travels on top of a meta-stable hillslope could conceivably contribute to failure by loading the slope with additional weight and scouring of vegetation. Hence, equation (3) only applies to those hillslopes where additional failures beneath moving landslide debris is unlikely. The hillslope gradient, in combination with underlying lithology, slope length, soil thickness, soil mechanical strength, rooting strength, and porosity that defines such potentially unstable areas would likely vary between regions or watersheds. Most shallow slope failures occur on hillslopes in excess of about 36° (73%) and often in convergent areas (Dragovich et al., 1993). Failure on non-convergent areas occur at an even higher slope thresholds (Sekiu Watershed Analysis; Acme Watershed Analysis). In the Acme WAU (TFW Watershed Analysis, in progress), shallow failures on planar slopes typically occur on slopes in excess of 40 degrees. It is assumed for the present application that a slope threshold over which failures could be triggered by landslide debris running over the surface should have be somewhat less than 40^0. Buchanan (1988) found a failure apparently triggered by impacts by moving landslides debris on a slope of 37^0 in the Chuckanut formation. Hence, an appropriate slope threshold above which failures might be anticipated by the runout of landslide debris may be on the order of 33 to 37 degrees (65 – 75%). This value could be adjusted based on site-specific field data. Therefore, the landslide runout model described above should not be applied to hillslopes mantled by thin soils (3 to 6 feet) much in excess of 35 degrees (70%), unless site-specific data is available. Additionally, hillsides containing mature forests (including partial cuts) which provide rooting strength may be a factor in increasing the slope threshold, while clearcut slopes may cause a lowering of the slope threshold.

The landslide runout model described above does not explicity account for momentum which is based, in part, on the velocity of the landslide as it encounters a lower gradient area. It is difficult to predict or anticipate the velocity of a moving landslide thereby making estimates of landslide momentum problematic. Spreading and thinning of landslide debris as represented in the Coulomb-Viscous model allows a landslide to travel until all of the debris is deposited to some critical depth. By this approach, the model described here implicitly accounts for some degree of momentum which would cause a similar type of spreading and thinning.

The predicted range of runout distance (Figure 3) appears to be in general agreement with transport distances observed on non-convergent hillslopes (Collins et al., 1994; Fannin and Rollerson, 1993). Ideally, field data on landslide runout on non-convergent hillslopes could be used to test, and if necessary, modify the predicted runout length of landslides.

To aid in field use, the model predictions have been presented in tabular form for a variety of slope gradient classes and landslide volumes (Tables 1 and 2). In some instances, more than one hillslope gradient will be encountered along a potential landslide runout path. The model outlined here can be applied in such cases, although a weighted average slope gradient must be estimated to calculate the critical thickness. Estimating a weighted slope gradient {(slope 1 * slope distance 1 + slope 2 * slope distance 2)/total slope distance} would require knowledge of the deposition volume along the initial runout path to determine the volume available to be spread out over the other portion of hillslope. This would require calculating an analytical solution. To estimate a weighted slope gradient in the field, an initial conservative estimate for potential runout could be used to define the slope length over which to estimate the average gradient (e.g., runout distance using a large landslide volume and steeper slope gradient). The weighted average slope gradient can then be used in Tables 1 or 2 to establish the appropriate critical thickness and therefore the predicted runout of debris on non-convergent hillslopes. Preliminary calculations indicate that weighted average slope gradients can be used to estimate potential landslide runout.

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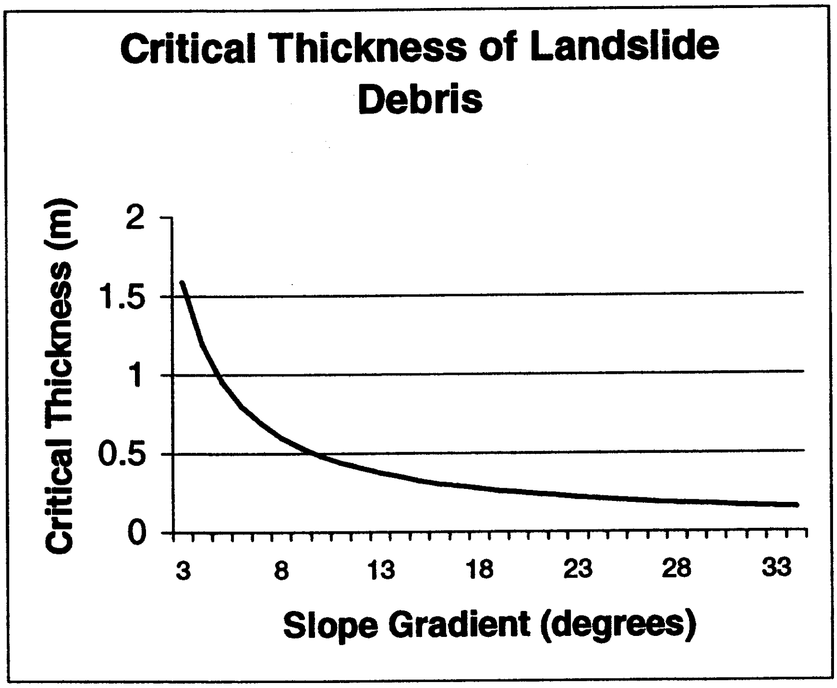


Figure 1. Critical thickness of landslide debris according to hillslope gradient based on estimates of yield strength and unit weight of material for liquified landslide debris using (1).

Geometry of Landslide Runout

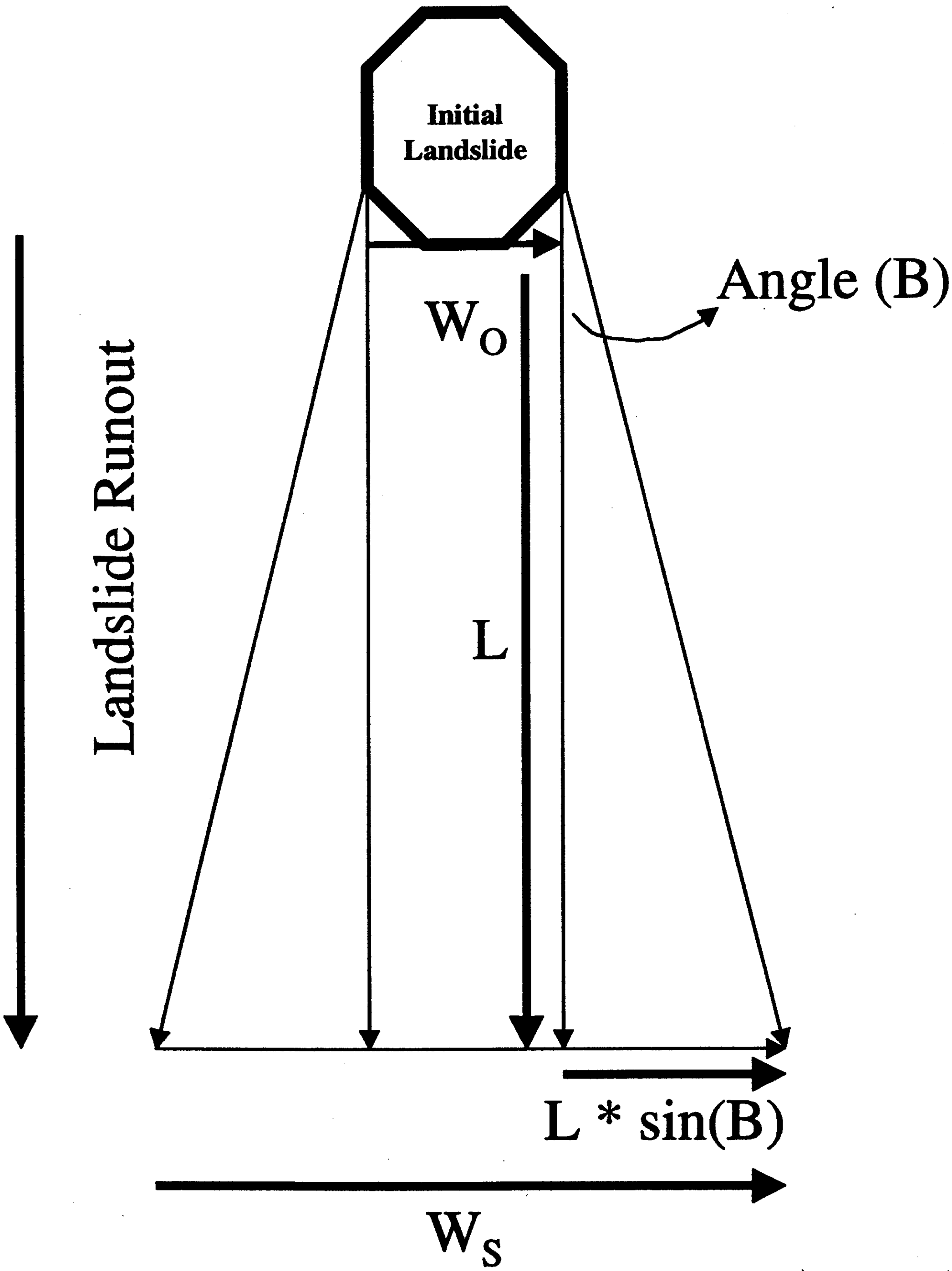
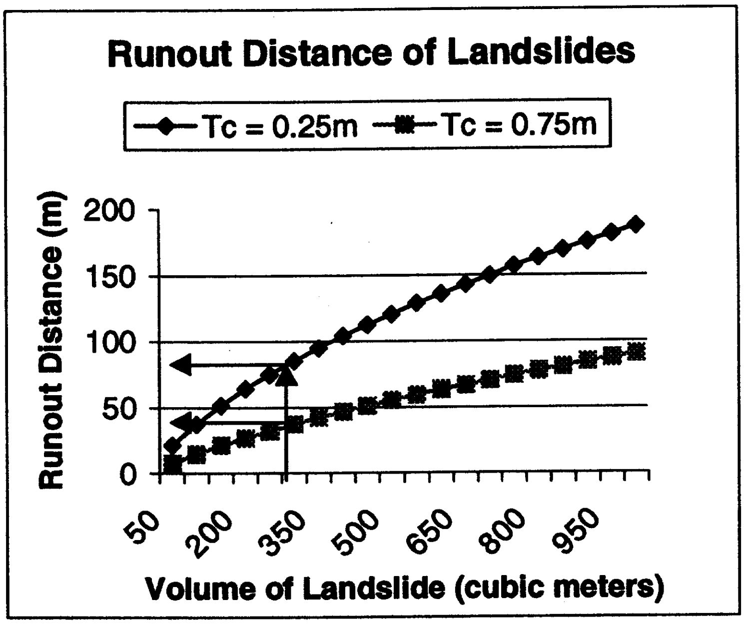


Figure 2. Idealized flow geometry of moving landslide debris on non-convergent hillslopes.



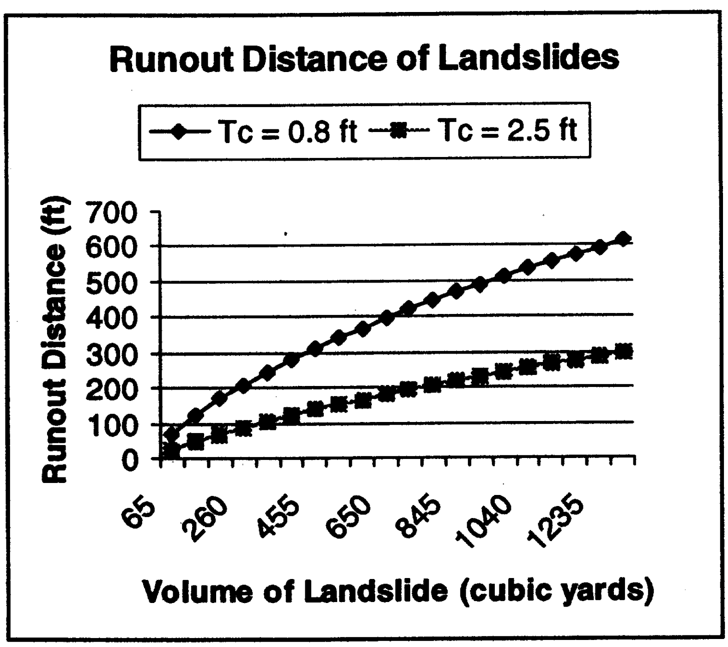


Figure 3. Predicted runout distances of landslide debris on non-convergent hillslopes less than 35 degrees (70%). Runout distance increases when critical depth of debris decreases on steep slopes (Tc = 0.25m). On lower gradient slopes where depths of landslide debris are thicker (Tc = 0.75m), runout distance will be less. The case is shown for a characteristic landslide volume of 350 m^3; runout is predicted to vary between 40 and 80 m (130 – 260 ft). Top figure in metric units bottom in English units.

Table 1. Landslide runout (m) as a function of volume for several hillslope gradients and corresponding critical thicknesses (Tc).							
Gradient (deg)	**5**	**10**	**15**	**20**	**25**	**30**	**35**
Tc (m)	0.956143	0.479898	0.321975	0.24365	0.197183	0.166667	0.145287
Volume (m^3)							
50	6.18	11.73	16.77	21.37	25.57	29.40	32.88
100	11.77	21.65	30.25	37.86	44.68	50.80	56.31
150	16.92	30.40	41.83	51.80	60.63	68.50	75.55
200	21.72	38.32	52.15	64.09	74.61	83.94	92.27
250	26.23	45.61	61.55	75.22	87.20	97.81	107.25
300	30.50	52.40	70.23	85.45	98.75	110.51	120.95
350	34.56	58.78	78.34	94.98	109.49	122.29	133.66
400	38.44	64.81	85.98	103.94	119.56	133.33	145.55
450	42.16	70.55	93.23	112.41	129.08	143.76	156.77
500	45.75	76.04	100.13	120.47	138.12	153.66	167.42
550	49.21	81.30	106.73	128.17	146.75	163.10	177.58
600	52.55	86.36	113.07	135.55	155.03	172.15	187.31
650	55.79	91.25	119.18	142.66	162.99	180.86	196.66
700	58.94	95.98	125.08	149.52	170.67	189.25	205.67
750	62.01	100.56	130.79	156.16	178.09	197.35	214.39
800	64.99	105.01	136.33	162.59	185.29	205.21	222.82
850	67.90	109.33	141.72	168.84	192.27	212.83	231.01
900	70.74	113.55	146.95	174.91	199.06	220.24	238.97
950	73.52	117.66	152.06	180.83	205.67	227.46	246.71
1000	76.24	121.68	157.04	186.60	212.12	234.49	254.27

Table 2. Landslide runout (ft) as a function of volume for several hillslope gradients and corresponding critical thicknesses (Tc).							
Gradient (deg)	**5**	**10**	**15**	**20**	**25**	**30**	**35**
Tc (ft)	3.136149	1.5740654	1.056078	0.799172	0.6467602	0.5466678	0.476541
Volume (yd^3)							
65	20.28	38.51	55.05	70.14	83.91	96.48	107.92
131	38.64	71.06	99.27	124.26	146.63	166.73	184.80
196	55.55	99.79	137.28	170.00	198.97	224.81	247.92
262	71.30	125.78	171.14	210.34	244.83	275.47	302.78
327	86.09	149.69	201.98	246.84	286.16	320.98	351.96
392	100.10	171.97	230.47	280.42	324.07	362.65	396.92
458	113.42	192.89	257.09	311.70	359.30	401.31	438.60
523	126.16	212.69	282.16	341.08	392.34	437.54	477.62
589	138.38	231.53	305.93	368.87	423.57	471.74	514.43
654	150.13	249.52	328.58	395.32	453.24	504.22	549.38
719	161.48	266.79	350.25	420.59	481.58	535.22	582.71
785	172.46	283.41	371.06	444.83	508.74	564.92	614.64
850	183.10	299.44	391.10	468.15	534.86	593.47	645.33
916	193.44	314.95	410.46	490.66	560.05	621.00	674.91
981	203.49	329.99	429.21	512.44	584.41	647.61	703.49
1046	213.28	344.59	447.38	533.54	608.01	673.38	731.18
1112	222.83	358.79	465.04	554.03	630.92	698.40	758.04
1177	232.16	372.62	482.23	573.97	653.20	722.71	784.15
1243	241.28	386.11	498.97	593.38	674.89	746.39	809.57
1308	250.20	399.29	515.32	612.32	696.05	769.47	834.35

APPENDIX 3-2

(DNR Form A-2) **MWMU # 1**

Description: The most landslide-prone area of the Acme WAU and the source of many long run-out debris flows and dam-break floods.

Materials: colluvium predominantly of Chuckanut sandstone origin.

Landform: Bedrock hollows and inner gorges of first- and second-order channels.

Slope: >/= 36° in convergent areas; >/= 40° on planar or divergent slopes.

Elevation: Variable.

Total Area: MWMU #1 is a variable width zone (approximately 30 to 50 m wide) that encompasses bedrock hollows. The zone width along inner gorges may be greater.

Mass Wasting Processes: Shallow landslides and debris flows; may initiate dam-break floods in third- and higher-order channels.

Forest Practice Sensitivity: Hillslopes located within MWMU #1 are susceptible to both timber harvesting and road building. Timber harvesting decreases the stability of these marginally-stable slopes by reducing the cohesion of tree roots. Roads in this map unit may: (i) create areas of concentrated drainage and thus reduced hillslope stability; (ii) overload already marginally stable slopes with sidecast material, thus reducing slope stability; (iii) oversteepen cut-bank slopes (>40°); and (iv) reroute and concentrate drainage. MWMU #1 appears to be most susceptible to logging roads in particular road fill failures and road drainage piracy.

Delivery: Delivery to fish-bearing channels and/or occupied fans.

Delivery Criteria: Benda and Cundy, 1990; Collins et. al., 1994, and field observations during the analysis.

Delivered Hazard Rating: HIGH.

Confidence: High

(DNR Form A-2) **MWMU # 2**

Description: An area of very steep slopes with thin soils that commonly fail by shallow landslides. Small, sporadic deep-seated landslides are also possible, particularly in Jones Creek. Deposits may trigger dam-break floods.

Materials: colluvium predominantly of Chuckanut sandstone origin.

Landform: Inner gorges of second- and higher-order channels including all slope forms, but convergent areas the most potentially unstable.

Slope: >/= 36° in convergent areas; >/= 40° on planar or divergent slopes.

Elevation: Variable.

Total Area: variable width zone.

Mass Wasting Processes: Shallow landslides, debris flows, and initiation sites of dam-break floods.

Forest Practice Sensitivity: Hillslopes located within MWMU #2 are susceptible to both timber harvesting and road construction. Timber harvesting can decrease the stability of these slopes by reducing the cohesion of tree roots. In addition, cable yarding logs over this area may disturb the ground and stumps which may contribute to failure. Roads in this map unit may: (i) create areas of concentrated drainage; (ii) overload already marginally stable slopes (sidecast material); (iii) oversteepen cut-bank slopes (>40°);and (iv) reroute and concentrate drainage.

Delivery: Delivery to fish-bearing channels and/or occupied/debris fans.

Delivery Criteria: Benda and Cundy, 1990; Collins et. al., 1994, and field observations during the analysis.

Delivered Hazard Rating: HIGH.

Confidence: High.

(DNR Form A-2) **MWMU # 3**

Description: Dispersed shallow landslides and debris flows within hollows and some planar topography within broad planar slopes of hillslope gradient >31°.

Materials: colluvium predominantly of Chuckanut sandstone origin.

Landform: Broadly planar hillslopes containing unmapped areas of MWMU #1. Also contains >/=36° planar topography and 31 - 35° convergent topography that can be landslide prone.

Slope: >31°.

Elevation: Variable.

Mass Wasting Processes: Shallow landslides and debris flows. Debris deposits can initiate dam-break floods.

Forest Practice Sensitivity: Hillslopes located within MWMU #3 are susceptible to both timber harvesting and road building although to a lesser degree compared to MWMU #1 and 2. Similar sensitivity to MWMU #2. In addition, road fill and landing failures may translate over this unit and trigger failures in steeper, higher hazard areas (inclusions of MWMU #1).

Delivery: Delivery to fish-bearing channels and/or occupied fans.

Delivery Criteria: Benda and Cundy, 1990; Collins et. al., 1994, and field observations during the analysis.

Delivered Hazard Rating: HIGH or MODERATE. Non-convergent hillslopes between 31 and 39° are considered moderate hazards. Non-convergent slopes in excess of 40° (84%) and with a high potential for delivery should be considered a high hazard. MWMU #3 contains unmapped inclusions of MWMU #1 (i.e. high hazard areas) and 31 - 35° hollows (moderate hazard) which requires site specific field surveys to locate.

Confidence: High.

(DNR Form A-2) MWMU # 4

Description: An area of very steep slopes with thin soils that commonly fail by shallow landslides. Small, sporadic deep-seated landslides are also possible, particularly in Jones Creek. Deposits may trigger dam-break floods.

Materials: colluvium predominantly of Chuckanut sandstone origin.

Landform: Inner gorges of second- and higher-order channels including all slope forms, but convergent areas the most potentially unstable.

Slope: >/= 36; all slope forms with convergent and planar forms the most potentially unstable.

Elevation: Variable.

Total Area: variable width zone.

Mass Wasting Processes: Shallow landslides, debris flows, and initiation sites of dam-break floods.

Forest Practice Sensitivity: Hillslopes located within MWMU #4 are susceptible to both timber harvesting and road construction. Timber harvesting can decrease the stability of these slopes by reducing the cohesion of tree roots. In addition, cable yarding logs over this area may disturb the ground and stumps which may contribute to failure. Roads in this map unit may: (i) create areas of concentrated drainage; (ii) overload already marginally stable slopes (sidecast material); (iii) oversteepen cut-bank slopes (>40°);and (iv) reroute and concentrate drainage.

Delivery: No delivery to fish-bearing channels and/or occupied fans.

Delivery Criteria: Benda and Cundy, 1990; Collins et. al., 1994, and field observations during the analysis.

Delivered Hazard Rating: LOW.

Confidence: High.

(DNR Form A-2) **MWMU # 6**

Description: Failures of bedrock slabs contained within the Devils slide area. Large fractures in bedrock characterize this area of "mountain splitting".

Materials: Marine sedimentary rocks - Chuckanut formation.

Landform: Complex topography including ridges, benches, steep hillslopes, first- and second-order channels - all slope forms (convergent, divergent, and planar).

Slope: >/= 30°.

Elevation: Variable.

Mass Wasting Processes: Predominantly slab failures in bedrock but can include shallow colluvial failures and debris flows (i.e. inclusions of MWMU #1 and #2).

Forest Practice Sensitivity: The sensitivity of map unit #6 (large bedrock slab failures) to forestry activities cannot be determined empirically because of the lack of clearcut activity coinciding with available aerial photographs. From a theoretical perspective, timber harvest should not affect the stability of the Devil's Slide, since the sliding mechanism involves large tensional forces in bedrock (i.e. mountain splitting) that should be little effected by rooting strength. Road construction, however, involving blasting and removal of bedrock, could change the distribution of forces in the bedrock and therefore further weaken areas of the Devil's slide. An analytical analysis could be conducted that would better quantity the effects of forestry activities on the Devil's Slide.

Delivery: Delivery to base of cliffs and possible to some occupies fans.

Delivery Criteria: Field observations of rock debris at base of cliffs.

Delivered Hazard Rating: Map unit #6 with delivery to public works and fish habitat is a high hazard with respect to road construction (all slope gradients and slope forms), and a moderate hazard with respect to timber harvest alone (see Section 3.5); with no delivery to fish-bearing waters it is a low hazard. An analytical analysis of deep-seated bedrock landsliding could change the hazard ratings.

Confidence: Moderate.

(DNR Form A-2) **MWMU # 7**

Description: Steep diverse topography that contains elements of the Devils slide (MWMU #6), and MWMU #1, 2, and 3. Forest canopy precluded detailed mapping of individual landslide-prone hollows and first- and second-order channels. Hence, the unit is broadly mapped. Requires field identification of landform and landslide potential.

Materials: Sandstone bedrock and colluvium predominantly of Chuckanut sandstone origin.

Landform: All slope forms including unmapped hollows and small inner gorges and may contain part of MWMU #6.

Slope: >/= 30°.

Elevation: Variable.

Mass Wasting Processes: Shallow landslides, small debris flows, and bedrock slab failures.

Forest Practice Sensitivity: Applies to areas of MWMU #1,2, and 3: Hillslopes located within MWMU #7 are susceptible to both timber harvesting and road building. Timber harvesting decreases the stability of these marginally-stable slopes by reducing the cohesion of tree roots. Roads in this map unit may: (i) create areas of concentrated drainage and thus reduced hillslope stability; (ii) overload already marginally stable slopes with sidecast material, thus reducing slope stability; (iii) oversteepen cut-bank slopes (>40°); and (iv) reroute and concentrate drainage. MWMU #7 appears to be most susceptible to logging roads in particular road fill failures and road drainage piracy.

Applies to areas of bedrock failures: The sensitivity of map unit #7 (large bedrock slab failures) to forestry activities cannot be determined empirically because of the lack of clearcut activity coinciding with available aerial photographs. From a theoretical perspective, timber harvest should not affect the stability of the Devil's Slide, since the sliding mechanism involves large tensional forces in bedrock (i.e. mountain splitting) that should be little effected by rooting strength. Road construction, however, involving blasting and removal of bedrock, could change the distribution of forces in the bedrock and therefore further weaken areas of the Devil's slide. An analytical analysis could be conducted that would better quantity the effects of forestry activities on the Devil's Slide.

Delivery: Delivery to fish-bearing channels and/or occupied fans in some locations. No delivery to resources in other locations. Delivery must be determined on a site-specific basis..

Delivery Criteria: Benda and Cundy, 1990; Collins et. al., 1994, and field observations during the analysis.

Delivered Hazard Rating: HIGH.

Confidence: Moderate.

(DNR Form A-2) **MWMU # 8**

Description: A large area of topography less than or equal to 30° with landsliding being uncommon to non-existent. Includes locally steeper areas with a higher likelihood of failure but that does not deliver to public resources. Hillslopes, valley floors, and ridge tops mainly south of McCarty Creek basin.

Materials: colluvium predominantly of phyllite and Chuckanut sandstone origin.

Landform: Unit is composed of hillslopes (<30°), valley floors (terraces, floodplains, and fans), and ridge tops; also includes locally steeper areas that do not deliver.

Slope: </= 30°.

Elevation: Variable.

Mass Wasting Processes: Mass wasting is rare to non-existent. Small sporadic deep-seated landslides may occur (unmapped); these need to be identified in the field - see prescriptions.

Forest Practice Sensitivity: Not sensitive to forest practices with respect to mass wasting.

Delivery: No delivery to fish-bearing channels and/or occupied fans.

Delivery Criteria: Benda and Cundy, 1990; Collins et. al., 1994, and field observations during the analysis.

Delivered Hazard Rating: LOW.

Confidence: High.

(DNR Form A-2) MWMU # 9

Description: Active and dormant deep-seated landslide terrain. Sliding along rotational failure planes but shallow landsliding along over-steepened toes is likely. Failures into Jones Creek may trigger dam-break floods. Dormant areas characterized by hummocky topography and evidence of past failures. In some cases, tipped and deformed trees and small tension cracks (centimeters) indicate slow deformation. Active areas characterized by large ground ruptures (meters) and recent displacement of soil blocks or groups of blocks. In addition, active failures may be recognized by fresh slide scarps and downed trees.

Materials: Colluvium predominantly of phyllite origin.

Landform: Hillslopes, commonly hummocky topography. Benches are likely. Deep soils and springs may characterize failure sites.

Slope: >/= 20°; highly variable.

Elevation: Variable.

Mass Wasting Processes: Small to large deep-seated landsliding. Landslides generally most active near toes along channels and immediately upslope. Deep-seated landslides may also be located in MWMU #2 in the Jones Creek basin, and in some cases they are unmapped. The deep-seated landslides may be the largest sediment source for the Jones Creek fan. High sediment delivery ratio.

Forest Practice Sensitivity: It is also not certain to what extent forestry activities affect the stability of the deep-seated landslide centered in Jones Creek (map unit #9). In one instance, a ground rupture along the perimeter of an existing slide scarp was detected in this landform in a clearcut (1991 photo), but it is uncertain to what extent harvest was involved in the slide reactivation. In addition, sediment mobility and delivery would have to be considered on a site specific basis to define a hazard for such slides. The area in the deep-seated slide with the highest potential to be affected by forestry activities is the inner gorge (map unit #2 - already designated as highly sensitive to forestry activities, see above).

Delivery: Delivery to base of cliffs and possibly to some occupied fans.

Delivery Criteria:

Delivered Hazard Rating: Map unit #9 Individual deep-seated landslides that show signs of being recently active and that deliver sediment to public works or fish habitat is ranked as a high hazard. Other deep-seated slide areas that appear to have been dormant for periods of centuries are ranked as moderate with respect to timber harvest alone, and a high hazard with respect to road construction where blasting or large removal of sediment is anticipated.

Confidence: Moderate.

(DNR Form A-2) **MWMU # 10**

Description: A narrow zone of moderate gradient topography that has a potential for limited shallow landsliding, and can also include unmapped small deep-seated failures.

Materials: Colluvium from phyllite.

Landform: topography adjacent to the inner gorge; includes broadly convergent areas.

Slope: 31 - 35°.

Elevation: Variable.

Mass Wasting Processes: Shallow landslides and debris flows, and to a lesser extent small, sporadic deep-seated failures.

Forest Practice Sensitivity: This unit, because of deep soils and moderate gradients, is probably most sensitive to logging roads through the process of fill failures, and road drainage piracy and diversions. Because unmapped deep-seated landslides can occur in this unit, road layout and construction engineers should be aware of the risk of reactivating deep-seated landslides. Reactivation can occur by undercutting the toe of failures by machinery and placing additional flow into the slide by road drainage structures.

Delivery: Possible to occupied fans.

Delivery Criteria: Field observations.

Delivered Hazard Rating: Moderate.

Confidence: Moderate.

DNR Form A-3

MWMU #1	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road	18			35				53
Clearcut	10			8				18
Young Forest								0
Mature Forest	3			2				5
Alpine								0
Other Landslides								0
N/A								0
Unknown								0
Total	31	0	0	45	0	0	0	76

DNR Form A-3

MWMU #2	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road	2			3				5
Clearcut	9			2				11
Young Forest				1				1
Mature Forest	9	4						13
Alpine								0
Other Landslides	2							2
N/A		4						4
Unknown								0
Total	22	8	0	6	0	0	0	36

DNR Form A-3

MWMU #3	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road	6			11				17
Clearcut	2			2				4
Young Forest				2				2
Mature Forest	2			2				4
Alpine								0
Other Landslides								0
N/A								0
Unknown								0
Total	10	0	0	17	0	0	0	27

DNR Form A-3

MWMU #4	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road								0
Clearcut								0
Young Forest								0
Mature Forest								0
Alpine								0
Other Landslides								0
N/A								0
Unknown								0
Total	0	0	0	0	0	0	0	0

DNR Form A-3

MWMU #5	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road								0
Clearcut	2							2
Young Forest								0
Mature Forest								0
Alpine								0
Other Landslides	1							1
N/A								0
Unknown								0
Total	3	0	0	0	0	0	0	3

DNR Form A-3

MWMU #6	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road								0
Clearcut				1				1
Young Forest								0
Mature Forest	10			1				11
Alpine								0
Other Landslides								0
N/A								0
Unknown								0
Total	10	0	0	2	0	0	0	12

DNR Form A-3

MWMU #7	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road	3							3
Clearcut	15							15
Young Forest								0
Mature Forest	2							2
Alpine								0
Other Landslides								0
N/A								0
Unknown								0
Total	20	0	0	0	0	0	0	20

DNR Form A-3

MWMU #8	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road	7			1				8
Clearcut	4			2				6
Young Forest		1						1
Mature Forest	1		1	2				4
Alpine								0
Other Landslides								0
N/A								0
Unknown								0
Total	12	1	1	5	0	0	0	19

DNR Form A-3

MWMU #9	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road								0
Clearcut								0
Young Forest								0
Mature Forest								0
Alpine								0
Other Landslides								0
N/A		1						1
Total	0	1	0	0	0	0	0	1

DNR Form A-3

MWMU #10	Shallow Rapid	Deep Seated	Debris Flow	Shallow Rapid/Debris Flow	Rockfall/ Snow Avalanche	Rockfall	Unknown	Total
Road								0
Clearcut								0
Young Forest								0
Mature Forest								0
Alpine								0
Other Landslides								0
N/A								0
Unknown								0
Total	0	0	0	0	0	0	0	0